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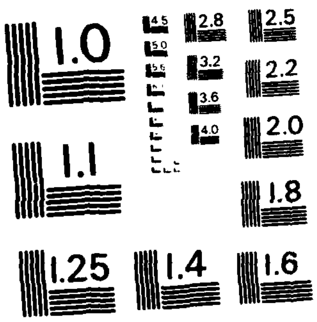
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CAORF 42-8106-02

CAORF TECHNICAL REPORT

SIMULATION EXPERIMENT

MANEUVERING RESPONSE

DEPARTMENT OF TRANSPORTATION

MARITIME ADMINISTRATION
OFFICE OF RESEARCH AND DEVELOPMENT

NATIONAL MARITIME RESEARCH CENTER
KINGS POINT, NEW YORK 11024

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This experiment was established to examine differences in ship handling performance of pilots transiting a narrow waterway on ships that exhibit distinctly different inherent maneuvering characteristics. The experiment was conducted using sixteen experienced pilots on four ships (all 80,000 DWT tankers) which exhibited distinctly different inherent maneuvering characteristics. The statistical analyses showed that with practically every ship performance measure that was employed, a significant ship-difference was found; with the most unstable vessel showing poorer performance and the stable vessel indicating better results. Three distinct areas of the test scenario (which was based on the SNAME "ABC Harbor") were found to cause major difficulties; namely, when turn effects and wind current sets were additive. It was determined, thorough structured debriefing, that the pilots were aware of the differences in transit performance difficulty. In spite of this, the experiment has shown that with comparable ship familiarization on each of the "new" vessels, the piloted performance on ships having different inherent maneuvering characteristics was variable.

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Current	Stability
Maneuverability	Wind
Pilot	

17b Identifiers/Open-Ended Items

17c. COSATI Field/Group

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CAORF

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SIMULATION EXPERIMENT

MANEUVERING RESPONSE

Prepared By

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EXECUTIVE SUMMARY

MANEUVERING RESPONSE EXPERIMENT

BACKGROUND

Vessels with different ship geometries and propulsion characteristics normally exhibit different levels of inherent stability and turning capabilities. When these different ships are subjected to such standard maneuvering testing procedures as turning circles, crash stops, Z maneuvers, etc., there is often a wide range of variability in the resulting ship performances. The human controller must therefore accommodate this variability of ship handling characteristics, which is caused by the physical characteristics of the vessels themselves, to ensure the safe passage of his ship in all of the demanding conditions that are likely to be encountered. When such a mariner, i.e., pilot, boards a vessel with which he has had no previous experience, either a new design or at least one that is new to him, what is the resulting range of man-ship performance which is exhibited?

OBJECTIVES

The specific objectives of the Maneuvering Response Experiment were to:

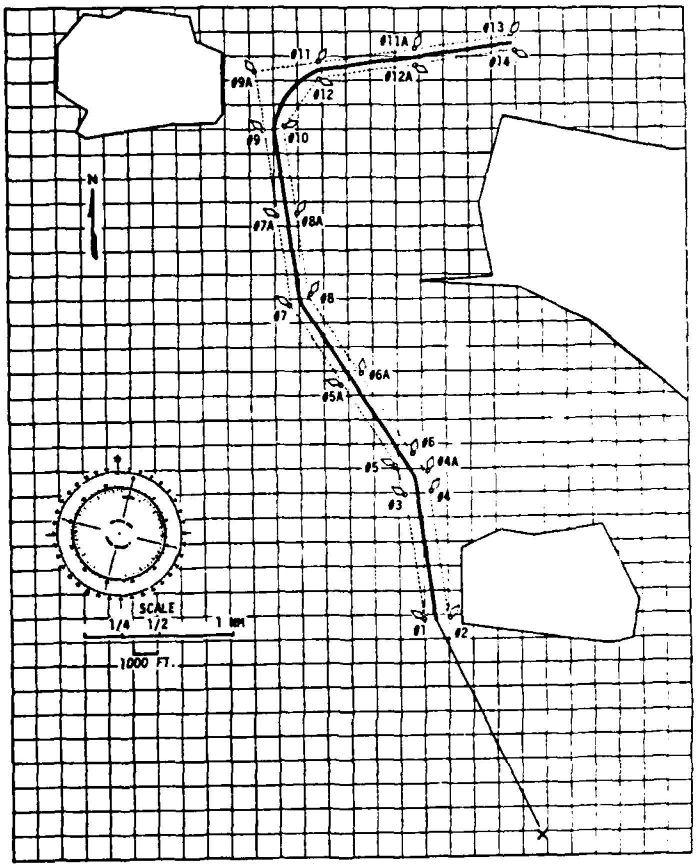
- o Determine the variations in ship handling performance which are attributable to differences in vessel inherent maneuvering characteristics, under conditions imposed by narrow channel transits.
- o Determine the impact on pilots' workload which is caused by the transit conditions and ship's characteristics.
- o Determine the pilots' perceptions of the ship handling difficulties which have been caused by the transit conditions as well as the inherent maneuvering characteristics of the vessels.

SCENARIO

All experiment runs were conducted in a waterway modeled after the "ABC" harbor described by the SNAME H-10 Panel on Controllability. The runs were made on four vessels with stabilities ranging from stable to unstable.

External conditions which most affect vessel control are water depth, current speed and direction, wind speed and direction, and harbor constraints, such as channel width, turns, etc. The "ABC" harbor (diagramed in Figure ES-1) includes a channel entrance with a cross-shear current, an S-turn consisting of two successive 25 degree turns, and a final right angle turn before an approach to an anchorage. Thus, it presents a series of realistic and representative requirements that a pilot/vessel might face on entering or leaving a port.

The wind, which was basically on the starboard beam for the major portion of the transit, tended to cause a starboard turning moment for all vessels. During the final leg, it became a head wind and tended to also turn the vessel when (depending on the vessel's crab angle) it fell on the starboard or port bow. Since the pilots' scenario directions were to slow the ship to two knots near the last buoys, this wind tended to have a large effect on the



Ship starting point Approx. .9nm from channel entrance
Latitude - 34° 0' 26" N
Longitude - 119° 55'10" W
Heading - 333°
Starting at full ahead, 60 rpm, maneuvering speed

Wind 25 knot average ± 10 knots, from: 73° - 78°

Cross shear current 2 knots - 252°

Leg 1 352°
1000' wide
2000 yards long
1 kt current - 352° Flood

Leg 2 327°
800' wide
2850 yards long
1 kt current - 327° Flood

Leg 3 352°
800' wide
2400 yards long
1 kt current "Transition"

Leg 4 82°
600' wide
2700 yards long
1 kt current - 82° Flood

Figure ES-1. "ABC" Harbor

ship's alignment with the desired track line as the ship's speed approached two to three knots. The current at the entrance of the channel caused a hard shear to port which, in turn, required close attention by the pilot. The combination of the previously noted head wind and a following current, as the ships slowed in the last leg, caused a situation which also required constant pilot attention. The geometry of the channel, along with the environmental conditions that were imposed, resulted in a transit which effectively challenged the pilots' ability to maintain control of their vessels. The effects of variability in maneuvering characteristics were therefore made more discernable than if a straightforward passage had been employed.

Subjects were told that for all runs the wind and current conditions in the harbor channel would not vary from those described, visibility would always be five miles, and no traffic would be encountered.

It was emphasized to each test subject that every effort should be made to follow a trackline in the center of the channel throughout each of the transits of the "ABC" harbor, including entering the harbor as close to the centerline as possible.

EXPERIMENT DESIGN

The experiment design was structured around two principle independent variables.

a) Ship Inherent Maneuverability (four levels)
   - Ship A Unstable
   - Ship B Moderately Unstable
   - Ship C Moderately Stable
   - Ship E Stable

b) Channel Legs (five levels)
   - Leg 1
   - Leg 2
   - Leg 3
   - 90^{o} Turn
   - Leg 4

These variables were combined in a Two-Factor Within Subject Design with each subject experiencing each of the four ships in each channel segment. A total of 64 runs comprised the experiment (16 subjects @ four runs), with the order of testing of ships randomized throughout.

Two complete sets of ANOVAS were performed making use of the data obtained from the experimental runs. The primary set of analyses were based on the variables of ship and channel legs. A secondary set was performed on the same data using run-order and channel legs as the variables under comparison. The "A" variable (RUN NUMBER) was also at four levels for this second set of analyses.

PERFORMANCE MEASURES

Ten performance measures were assessed via the Analysis of Variance in the experiment.

1 - Ship Velocity Over the Ground (VOS)
2 - Swept Path
3 - % of Time VOS Over Seven Knots
4 - Average Off-Track Deviation ($\bar{X}$)
5 - Boundary Penetrations (Transformed)
6 - Boundary Penetrations (Non-Transformed)
7 - Root Mean Square of Off-Track Deviation (X_{RMS})
8 - Total Rudder Command Rate

9 - Total Command Rate
10 - Consistency (Standard Deviation of Off-Track Deviation)

In all cases these measures were computed across five sections of the test channel. Eleven additional measures were analyzed for ship-order effects and run order effects by using a second ANOVA model. These measures were based on happenings which occurred once per run, either "totals" for a measure previously analyzed across the leg variable, or an item which occurred at only one point in the channel. These measures were:

11 - VOS (Total)
12 - Swept Path (Total)
13 - VOS at End of Run
14 - % of Time VOS Over Seven Knots (Total)
15 - $\bar{X}$ (Total)
16 - Boundary Penetrations - Transformed (Total)
17 - Boundary Penetrations - Non Transformed (Total)
18 - X_{RMS} (Total)
19 - Transit Time for Legs 2 through 90° Turn
20 - Distance Off Buoy #1
21 - Consistency (Total)

RESULTS

Ship Handling

There were four vessels that were compared in the experiment, with inherent maneuvering characteristics which varied from stable (Ship E) to unstable (Ship A). Ship C was marginally stable, while the stability of Ship B fell between that of Ship A and Ship C. Various statistical and non-statistical analyses were performed to assess the ship handling difficulties that were imposed on the sample group of pilots by the variability in handling characteristics, resulting in the following overview; Ship A was by far the most difficult ship to handle, causing the most problems, and Ship E was the easiest, allowing the pilots to display the best performance of all. Performance on Ships B and C tended to also fall into an order which correlated with stability, but not to the marked degree as with the other two vessels.

There were three main harbor areas that tended, as designed, to cause the pilots difficulty; namely, the channel entrance (subsequent to a high shear current), a 25° starboard turn (which reinforced a starboard beam wind), and a 90° starboard turn (with a following current and a wind which changed from starboard beam to slightly off the bow).

The statistical analyses that are functions of distance off desired track contributed heavily to the overview noted above. Average off-track deviation ($\bar{X}$) and X_{RMS}, as well as consistency of track (X_{σ}), all indicated poorer performances on Ship A, and better performances on Ship E, especially in the legs which had been designed with the most difficult ship handling problems. Swept path, or the area which is "carved out" of the channel by the extremities of the ship, was wider for Ship A than for the other vessels. This performance trend was also observed for the measure of Boundary Penetrations, with the more unstable vessel tending to "side slip" at the turning areas of difficulty at a higher incident rate, and therefore more frequently moving out of the channel boundary limits.

A correlation analysis of performance difficulty with ship stability was also performed and the findings indicated that the ship handling displayed by half the sample correlated strongly

with ship stability, i.e., at a level of +0.950 or higher. The average correlation for the total group was +0.813, also quite strong.

Summary ground tracks for each ship, which averaged the performance of all the pilots on each of the ships, were also developed and indicated the difficulty encountered at the three specific areas, previously noted. The most unstable vessel (A) caused variable and, at some points, somewhat uncontrolled performance by the pilots, while the most stable ship (E) allowed them to transit the channel in an orderly manner.

Pilot Workload

The impact on pilot workload, caused by the transit conditions and inherent ship maneuvering characteristics, showed little to no effect. The findings indicate that there was either no relationship between workload and ship stability, or, that the parameters selected to measure this effect were inadequate or insensitive to the task. Judging by the numerous Boundary Penetrations that were in evidence, as well as the relationship of Boundary Penetrations to ship maneuvering capabilities, it would appear that there should have been a strong pilot-ship workload effect. The workload parameter *did* show a leg effect, which indicated increased pilot commands in the channel entrance leg and the 90° turn. This, however, occurred independently of the ship that was being conned.

Pilot Perceptions

Various performance measures and analyses *did* indicate that the ship handling characteristics of the sample pilot grouping varied, and that they were dependent on the stability/inherent maneuvering characteristics of the vessel being conned. To assure that the pilots were aware of their difficulties (and therefore presumably attempting to better their performances when they were having more difficulty), they were asked to subjectively rank the ships according to difficulty, after they completed their last data run. This information was analysed at the conclusion of the experiment and showed that the pilots were well aware of performance problems, showing a high positive correlation of perceived difficulty with the performance difficulties actually displayed. A high positive correlation of perception with the inherent maneuvering characteristics of the ships themselves was also found. Fourteen of the 16 subjects found Ship A to be the most difficult to handle while 12 ranked Ship E as moderately easy, easiest, or tied with another vessel for these lowest rankings. Approximately three-quarters of the group ranked Ships B and C as neither hardest nor easiest to handle.

Experimental Validity

During the early phases of the project every effort was made to structure the experimental conditions so that the explicit objectives of the experiment could be validly met. It was also decided, at that time, to question the test subjects during their final debriefings in an attempt to ascertain whether confounding influences (e.g., unrealistic requirements) existed. One question was posed to the pilots concerning the overall realism of the experimental task, a second was concerned with the desired track line that was used, and a third concerned itself with suggestions regarding additional tasks which might have brought out ship handling characteristics in a

superior manner. Responses to all three of these questions were positive; that is, the overall task was realistic, similar in general to home harbor conditions, the center line desired track was adequate, and no obvious need was expressed for meaningful changes to the experimental tasks.

By far the most significant finding was with respect to the number of runs which were required of each test subject, as well as whether or not two channel familiarization runs were adequate to familiarize the pilots with the experimental tasks that were to be performed on the simulator. The Run-Order analyses were conducted to ascertain if any effects could be discerned related to the order in which the ships were run. This would have indicated either fatigue effects or simulator learning effects. The results of the Run-Order analyses indicated the soundness of the experiment design. Essentially, none of the key performance measures showed a run-order effect compared with practically all of them showing a ship effect.

The implications of these findings indicate that confounding influences were minimized by the structure and conditions of the experiment design.

CONCLUSIONS

The basic question that this experiment had attempted to explore is concerned with a facet of "Pilot Lore." When asked about potential problems concerning the process by which they become familiar with vessels that they have not sailed before, experienced pilots commonly express the view that they can get the "feel" of a new ship very quickly after taking the conn. This "feel" is concerned with the ability to handle the vessel safely throughout the pilotage area and implies that the level of this acquired ability does not substantively vary for any ship that they may be required to pilot. The fact that this is accomplished in an efficient, professional manner is evidenced by statistics related to the high level of safe passages that do occur every year, under highly variable conditions. A question has therefore existed regarding the variability of this familiarization ability and the manner in which different vessels and different pilots affect the man/ship interaction which is displayed.

The experiment has shown that piloted performance on ships having different inherent maneuvering characteristics is variable, with the resulting performance on the more unstable vessel being poorer than on the marginally stable or stable ships. The pilots are aware that they are having more difficulty with the unstable ships but still display significantly different transit performance on them. It can therefore be inferred that this is happening in spite of their recognition of the situation and their attempts at alleviating the problem difficulties. Because of this, it is obvious that numerous harbor safety implications exist regarding the inherent maneuvering characteristics of existing and new ship designs.

Another interesting conclusion that can be drawn from this program is that the experiment has indicated the beginnings of a standard procedure that can be used to compare relative pilot ship handling capabilities on vessels with differing inherent maneuvering characteristics; with both existing vessels and, perhaps more importantly, new ship designs. A performance data base can be amassed, starting with the data obtained from this experiment, so that other vessels

can be used on the simulator in conjunction with additional pilots making additional experimental runs through the test scenario of the "ABC" Harbor. Subsequent analyses of the new data will allow the newer vessel to be ranked relative to the existing ships in the data base. This can be accomplished even prior to the actual construction of a new vessel, and is solely dependent on the generation of the necessary ship coefficients for use in the simulation of the vessel. Decisions regarding necessary maneuvering characteristics design changes can therefore be made much earlier in the design/construction sequence for new vessels through the use of this proposed procedural standard.

CHAPTER 1

INTRODUCTION

1.1 PURPOSE

This report presents the results of a Maneuvering Response experiment conducted at the Computer Aided Operations Research Facility (CAORF), Kings Point, New York. The study examined the differences in ship handling performance of pilots transiting a narrow waterway on ships which exhibited distinctly different inherent maneuvering characteristics. The specific objectives of the experiment were to:

o Determine the variations in ship handling performance which are attributable to differences in vessel inherent maneuvering characteristics, under conditions imposed by narrow channel transits.

o Determine the impact on pilots' workload which is caused by the transit conditions and ship's characteristics.

o Determine the pilots' perceptions of the ship handling difficulties which have been caused by the transit conditions as well as the inherent maneuvering characteristics of the vessels.

1.2 BACKGROUND

The influence of a ship's inherent controllability on the frequency of occurrence of collisions, groundings and rammings (CGR) has become a subject of research that has been given a high priority by both the U. S. Coast Guard and Intergovernmental Maritime Consultative Organization (IMCO).

For the past few years, the maritime research program at the Computer Aided Operations Research Facility (CAORF) has been addressing multiple issues concerned with vessel transit in harbors and narrow waterways. The work has been accomplished using the full capabilities of the CAORF Ship Maneuvering Simulator, including the fully instrumented ship's bridge and the computer generated visual imagery described in Appendix A. The focus of one research area - Piloted Controllability and Ship Maneuvering Response - has been concerned with investigations in which pilot/master behavior and related ship controllability factors are studied. CAORF has always made the study of the human/ship interactive performance one of its prime objectives. Satisfactory passage depends not only on the inherent characteristics of the ship itself, but also on the capabilities of the pilot and his helmsman, the harbor layout, and the existing natural environmental phenomena. In addition, piloted controllability depends on the effectiveness, accuracy and reliability of the various navigational aids. The caliber of shiphandling is, therefore, constrained not only by the ship's inherent maneuvering performance (completely independent of any human intervention) but also on the skill and experience of the operators.

It is extremely difficult to discern how many groundings, etc., in real life (not caused by equipment failures) can be attributed to the inherent controllability of the ship or by the human error in perception of the ship's capabilities. The groundings may have

been originated by the pilot not changing course in time or recognizing the presence of current or winds, etc. There is also a variability across the range of pilot ability/perception since some mariners have grounded while the majority have successfully transited without incident and seemingly without too much effort.

The study, which is reported herein, has looked into the capabilities of the pilot in overcoming ship characteristics that may be considered "poor." Whereas ships involved in all our experiments are simulations of real ships presently in operation, this study considers versions of an 80,000 DWT tanker ranging from very unstable to very stable. The variations in stability are realistic, however, and cover a wide spectrum of existing ships reported in the international literature.

Ship maneuverability is primarily important during the short but extremely critical period at the beginning and end of a long voyage. Many of the design features that can provide enhanced performance over the major part of the voyage in the deep ocean generally do not lead to improved maneuverability in shallow water. Conversely, designs that could provide increased maneuverability in harbors can lead to increased drag and, therefore, increased energy consumption. In addition, these latter design features can be more expensive to install, be more vulnerable to damage in confined waterways, and can also require dry docking for repairs. Some compromise must be reached between the overall economics of new design modifications and the degree of safety that results. Hydronautics, under contract with the USCG investigated an 84,000 DWT baseline ship and evaluated the effectiveness of various improvements in the ship design in reducing CGR casualties caused by lack of ship's inherent controllability. Their investigation indicated that attainable improvements in maneuvering performance were small, and never exceeded 20 percent.(1) As a result, the most promising techniques for operating safely despite poor inherent properties of existing ships would appear to be to use tugs in combination with lower speeds, and to consider turning rather than stopping where available space permits.

The performance of a ship, however, and particularly in narrow waterways, is not just dependent on the ship's inherent characteristics--the human at the controls plays an extremely important role. In this regard, the Port and Safety Act of 1978 required that the human performance aspects of ship operation be investigated as well as the more conventional standards of ship design and equipment and physical integrity. The impact of human performance on maritime safety has always been a primary objective of research at CAORF. It is well recognized that the experience and shiphandling capabilities of the human operator to varying degrees can overcome many of the deficiencies in his ships that he may experience while attempting to produce a good, safe passage. Although superficially his performance many appear to be independent of the ship characteristics, he may, in fact, be issuing a much different frequency of orders of different magnitudes dependent on the inherent qualities of the ships and may, therefore, be working under different, i.e., difficult, workload conditions. The present experiment was designed to investigate this question and to provide a realistic answer.

Steady state conditions are rarely achieved during any harbor transit, and it is the transient response of the ship in conjunction with the human feedback that is of prime importance during this phase of the passage. Ship

characteristics, such as steady state turning circle, and crash stopping distances are most important in collision avoidance extremis conditions, where the mariner is really in the process of losing control of the situation. However, it is possible that his ultimate maneuver was initially occasioned by other factors, such as a human error or misjudgement, and was not necessarily due to any environmental conditions or lack of own ship's maneuverability.

This present project presented the pilot with four variations of an 80,000 DWT tanker. These were:

1) A conventional 80,000 DWT tanker that is marginally stable and that has been tuned to compare favorably with real world trial data.

2) A variation of this tanker which is more stable than the ship that was based on real world trial data.

3) Two further variations of the first vessel, one that is moderately unstable and a second which is very unstable.

By this method, the pilots conned four 80,000 DWT tankers having characteristics that vary realistically within a broad spectrum and are similar to actual ships of all types and sizes. The linear hydrodynamic coefficients due to sway and rotation which are the determinants of the ship stability were selected using experimental information from Sweden(2) and Denmark(3) and others. The non-linear coefficients, which are essential in providing damping to the ship motion, were also varied systematically throughout the ships. The derivation of all these coefficients and the techniques that were used are described in Appendix B. The variations selected can be obtained by appropriate adjustments in draft and physical ship dimensions. However, concern was not with the ship design aspects themselves but more importantly with the "workload" imposed on the pilot by the differing ship handling qualities of his ships, in relation to the utimate performance, as indicated by various selected measures.

1.3 EXPERIMENT DESCRIPTION

The Maneuvering Response experiment has been designed to address several issues related to the effects of the vessel's inherent maneuvering characteristics in narrow waterways; namely, the resultant ship handling performance exhibited by a grouping of experienced pilots while transiting a restricted waterway on vessels with differing maneuvering capabilities, as well as the workload that these ship characteristics impose upon the pilots. A series of four vessels were selected for this purpose with maneuvering characteristics which cover the spectrum from stable to marginally stable to unstable. These ships have different turning, stopping and rudder control capabilities. The experiment compared the ship handling performance of a group of sixteen pilots that conned these four ships. The scenario that was used was the "ABC" Harbor containing representative bends, turns, winds, currents, widths and stopping requirements. Each pilot transited the channel once with each vessel so that data for four experiment runs were obtained from each pilot/test subject, for a total of 64 experiment runs. In addition, each pilot made two familiarization (non-data) runs on a fifth vessel prior to his experiment runs. The purpose of these preliminary runs was to allow the pilot to become familiar with the channel characteristics but not with any of the experiment's vessels.

Based on previous experiments run at CAORF, which were concerned with the effects of variations in ship characteristics caused by environmental factors, it was expected that the pilots might well overcome the differences in vessel's inherent maneuvering characteristics and display shiphandling performance during the transits which does not differ significantly between the ships. It was anticipated though that the effort required to accomplish this would vary significantly and that pilot workload would increase as the maneuvering characteristics became poorer. The primary performance measures for ship performance were deviation off desired track, swept path, number of penetrations of channel buoy lines by any portion of the ship, and ship speed. Individual track plots as well as average track per ship plots were also analyzed. The pilot work load assessments were made by analyses of frequency of rudder and RPM orders. In addition, analysis of subjective pilot assessments and perceptions were attempted by means of structured test subject debriefing questionnaires.

CHAPTER 2
METHODOLOGY

2.1 EXPERIMENT DESIGN

Each subject made six transits through the "ABC" harbor channel. The first two transits were for familiarization purposes and the remaining four were "experimental' runs. For these four transits, test subjects conned four different ships each differing in their inherent maneuvering characteristics. The particular sequence of exposure to the four different ships was counter-balanced across subjects according to the sequence illustrated in Table 2-1. It was thought that the randomization process would serve to control any effects on the main variables of the experiment which might be associated with a fixed order of presentation (e.g., learning, fatigue, etc.). Analyses were performed to ascertain if a so-called "Run Order" effect was present in spite of these precautions and the results are reported and discussed in Chapter 3.

The primary variable under investigation in the experiment was:

- o Ship Inherent Maneuverability (4 levels)
  - -Ship A - Unstable
  - -Ship B - Moderately unstable
  - -Ship C - Moderately stable
  - -Ship E - Stable

A secondary variable in the experiment was:

- o Channel Segments (5 levels)
  - In the entrance to the channel, leg 1, the pilot was required to deal with the two knot cross-shear current. This leg was used as a vessel familiarization phase and not used for analyses purposes.
  - In channel legs 2, 3 and 4, track-keeping was the primary concern.
  - In channel, leg 4, the pilot also prepared for the 90° turn (leg 5).
  - In the final leg of the channel (6), the pilot had to recover from the turn, and maintain the track line under the conditions imposed by wind and current while slowing the ship.

The design structure of this experiment was a Two-Factor Within Subject Design with each subject experiencing each of the four ships in each channel segment. The ANOVA model for the design is illustrated in Table 2-2 and enabled data analysis procedures to determine the individual effects of the independent variables and their interaction. The appropriate ANOVAS were used for all comparisons and were supplemented by Neuman-Keuls Multiple Comparison Procedures and t-tests using the appropriate error term for the ANOVA.

2.2 PERFORMANCE MEASURES

Comparative evaluation of track-keeping performance was accomplished using both system performance and pilot performance measures. Whereas system performance measures provided indices of ship state relative to ideal reference values, caused by pilot/ship interactions with the transit conditions, pilot performance measures revealed the pilots' procedures in accomplishing the passage.

TABLE 2-1. EXPERIMENT RUN SEQUENCE

Subjects	Transits					
	1	2	3	4	5	6
1	1	1	C	A	B	E
2	1	1	E	C	B	A
3	1	1	C	E	B	A
4	1	1	C	E	A	B
5	1	1	A	E	C	B
6	1	1	A	C	E	B
7	1	1	E	A	C	B
8	1	1	B	C	A	E
9	1	1	A	B	E	C
10	1	1	B	C	E	A
11	1	1	E	A	B	C
12	1	1	A	B	C	E
13	1	1	E	B	A	C
14	1	1	B	E	A	C
15	1	1	B	A	C	E
16	1	1	C	B	E	A

NOTE: Vessel 1 is used in the two familiarization runs only.

Vessels A, B, C and E are the four ships with different maneuvering capabilities to be used for the experiment runs.

2.2.1 System Performance Measures

The primary index of system performance was off-track deviation (X). The basic off-track deviation was determined by measuring the distance along a perpendicular line drawn between the ship center of gravity location and the desired track line. Various functions of X were used in the analyses including the average per leg ($\bar{X}$), the average per total channel ($\bar{X}_T$), the root mean square per leg (X_{RMS}) as well as the total channel root mean square (X_{RMS-T}). The standard deviation of X and X_T were also used.

For each run the off-track deviation as the ship passed the entrance buoys 1 and 2 (X_{1-2}) was calculated and subsequently analyzed.

Two measures which are related to X were also analyzed; boundary penetrations and swept path. The number of times a portion of the ship penetrated the channel limits was calculated and used for both leg and total channel comparison purposes, i.e.,

TABLE 2-2. ANOVA SOURCE TABLE - 2 FACTOR WITHIN SUBJECTS DESIGN

Source	Degrees of Freedom df	Mean Square MS	F
Subjects	15		
Ship (A)	3	SS A/3	MS A/MS ERROR A
Channel Segment (B)	4	SS B/4	MS B/MS ERROR B
A X B	12	SS AB/12	MS AB/MS ERROR AB
ERROR A	45	SS ERROR A/45	
ERROR B	60	SS ERROR B/60	
ERROR AB	180	SS ERROR AB/180	

boundary penetrations. In addition, the projection of the ship's geometry on a line perpendicular to the desired track is a measure of the skewness or crab angle that the ship had attained at every position of its transit. Variations in this skewness is a measure of the control exhibited during the passage. This swept path has a minimum value of ship width (125') when the longitudinal axis of the ship is parallel to the desired linear track line or parallel to the tangent to the curved desired track line. A maximum value of ship length (763') occurs when the ship is perpendicular to the desired track. The average swept path per leg as well as average per total channel were calculated and analyzed.

Additional measures were used to determine how well the pilot was able (or willing) to follow the scenario restrictions. Average speed over the ground per leg (VOS) and for the total channel (VOS-T) were calculated and compared. Percent of time that ship speed over the ground exceeded 7 knots as well as the speed at the end of the run (V_{13-14}) were also analyzed. The total time for the passages through legs 2, 3, 4 and the 90° turn were compared.

2.2.2 Pilot Performance Measures

Frequency of rudder orders and engine orders were recorded during each experiment run by the mate-on-watch. These data were used to assess pilots' workload as it related to different portions of the transit as well as the effects that the different maneuvering characteristics had on the test subject's concentration on the pilotage task. Total rudder orders per leg and rudder plus engine orders per leg were normalized to command rates per minute, for comparison purposes.

2.2.3 Difficulty of Performance Measure

Individual ground track plots were analyzed to attain a difficulty measure for each ship/pilot combination. This relative difficulty rating

was then used as a measure of run order effects and ship characteristics effects. It was also used as the basis of analyses related to the pilots' perception of difficulties that were being experienced.

2.3 VESSELS

The experiment required five ships with different inherent maneuvering characteristics for use by each of the pilot/test subjects. One vessel, the standard CAORF 30,000 DWT tanker, was used for the dual channel familiarization runs. This vessel has its bridge amidship and reacts like a steam turbine powered ship. Deepwater maneuvering characteristics for the 30,000 DWT tanker are indicated in Figure 2-1 and were shown to each pilot prior to his familiarization runs.

The four experiment runs for each pilot required the use of four additional ships, with different characteristics. Although the vessels' external geometric dimensions and bow configurations were the same, that of an 80,000 DWT tanker, the pilots were told that they would handle differently, as often occurs in actuality. These vessels also react like steam turbine powered ships but the 80,000 DWT tankers have the bridge at the stern. These vessels (A,B,C and E) exhibited different turning circles, stopping characteristics and stability criteria, which varied from stable to unstable; the latter was designated as Ship A while the former was Ship E. Ship C was marginally stable, and the stability of Ship B fell between that of Ship of A and Ship C. The necessary deepwater information for these vessels, similar to maneuvering data which is normally available to a pilot when he comes onto the bridge of a newly boarded ship, are given in Figures 2-2, 2-3, 2-4 and 2-5. Appendix B contains additional information related to the ship's design and stability characteristics.

The variability in maneuvering capability was obtained by several methods for this experiment including changes in effective length, ballast, draft, and shallow water effects for standard CAORF ship(s). The methods by which the characteristics were obtained were not relevant to the experiment objectives since the resulting maneuvering capabilities actually define the ship that was used. Any conclusions that are drawn from the experiment are relevant to ships with these characteristics and should hold for any vessels exhibiting these or similar characteristics. The variability in the characteristics could be caused by inherent design factors, such as geometry, hull configuration, rudder size or shape, etc. The transposition of the simulated characteristics into geometric ship parameter considerations was not the purpose of the present investigation and will be left to analyses through future off-line activities.

2.4 TEST SUBJECTS

This experiment required a total of 16 full branch harbor pilots. The only restriction placed on the selection of pilots for participation in this experiment was that they should have no prior experience with the CAORF model "ABC" harbor. The harbor model was used in two prior CAORF projects, Pilot Performance 1 and 2. To insure that all pilots had an equivalent experiential background with the "ABC" harbor, it was best to select only pilots with no prior experience with the harbor and supply this background familiarization as part of the procedure of the present investigation.

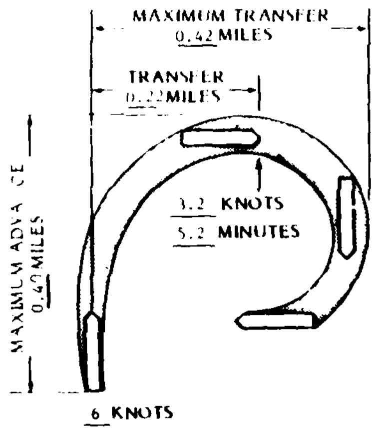
DEEP WATER MANEUVERING CHARACTERISTICS

CAORF LINES

S.S. THIRTY KAY

Turning Circle Diagram

FULL LOAD / HALF SPEED



FINAL DIAMETER 0.35 MILES

DRAFT FWD 34'7" DRAFT AFT 34'7"

Length	595.0'	(181.4m)
Beam	84.0'	(25.6m)
Draft	34.6'	(10.6m)
Displacement	37700	TONS
Capacity	30000	DWT

Maximum Rudder Angle	STARBOARD RIGHT 35 DEGREES	PORT LEFT 35 DEGREES

TIME AND DISTANCE TO CRASH STOP		
	Full Load	
Engine Order	**Time (Minutes)**	**Distance Miles**
Full Sea Speed	7.6	.87
Full Ahead	5.2	.37
Half Ahead	3.8	.19
Slow Ahead	2.3	.06

ENGINE ORDER / R.P.M. / SPEED		
Engine Order	**RPM**	**Speed (Knots) Full Load**
Full Sea Speed	120	17.4
Full Ahead	60	8.7
Half Ahead	40	5.8
Slow Ahead	20	2.9
Dead Slow Ahead	10	1.5
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	40	
Full Astern	60	**Time Full Ahead RPM to Full Astern** 150SECS

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather - 10 knots or less, calm sea.
2. No current.
3. Water depth three times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less Advance.
2. There is no appreciable difference in the time or distance of ADVANCE and TRANSFER when making a turn to port or starboard. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same, regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

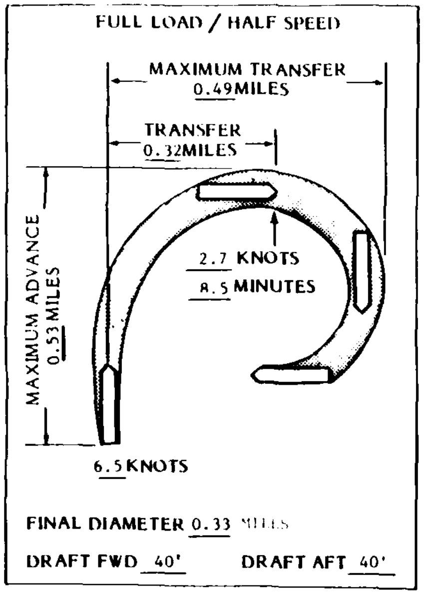
Figure 2-1. 30,000 DWT Tanker Maneuvering Characteristics

DEEP WATER MANEUVERING CHARACTERISTICS

CAORF LINES

S.S. EIGHTY KAY-A

Turning Circle Diagram



Length	763.9'	(232.6m)
Beam	125.0'	(38.1m)
Draft	40.0'	(12.2m)
Displacement	87142	TONS
Capacity	80000	DWT

Maximum Rudder Angle	STARBOARD RIGHT 35 DEGREES	PORT LEFT 35 DEGREES

TIME AND DISTANCE TO CRASH STOP		
Engine Order	**Full Load**	
	***Time* (Minutes)**	**Distance Miles**
Full Sea Speed	12.0	1.59
Full Ahead	8.5	0.67
Half Ahead	7.3	0.31
Slow Ahead	4.2	0.13

ENGINE ORDER / R.P.M. / SPEED		
Engine Order	**RPM**	**Speed (Knots) Full Load**
Full Sea Speed	120	19.5
Full Ahead	60	9.8
Half Ahead	40	6.5
Slow Ahead	20	3.3
Dead Slow Ahead	10	1.6
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	40	
Full Astern	60	**Time Full Ahead RPM to Full Astern** 150SECS

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather - 10 knots or less, calm sea.
2. No current.
3. Water depth three times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less Advance.
2. There is no appreciable difference in the time or distance of ADVANCE and TRANSFER when making a turn to port or starboard. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same, regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

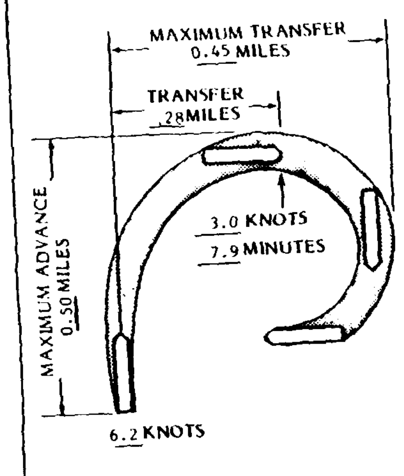
Figure 2-2. Ship A - 80,000 DWT Tanker Maneuvering Characteristics

DEEP WATER MANEUVERING CHARACTERISTICS

CAORF LINES

S.S. EIGHTY KAY-B

Turning Circle Diagram



Length	763.0'	(232.6m)
Beam	125.0'	(38.1m)
Draft	40.0'	(12.2m)
Displacement	87142	TONS
Capacity	80000	DWT

	STARBOARD RIGHT	PORT LEFT
Maximum Rudder Angle	35 DEGREES	35 DEGREES

TIME AND DISTANCE TO CRASH STOP		
	Full Load	
Engine Order	Time (Minutes)	Distance Miles
Full Sea Speed	15.7	1.93
Full Ahead	11.1	.81
Half Ahead	8.9	.46
Slow Ahead	4.1	.12

ENGINE ORDER / R.P.M. / SPEED		
Engine Order	RPM	Speed (Knots) Full Load
Full Sea Speed	120	18.6
Full Ahead	60	9.2
Half Ahead	40	6.2
Slow Ahead	20	3.1
Dead Slow Ahead	10	1.5
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	40	
Full Astern	60	Time Full Ahead RPM to Full Astern 150SECS

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather - 10 knots or less, calm sea.
2. No current.
3. Water depth three times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less Advance.
2. There is no appreciable difference in the time or distance of ADVANCE and TRANSFER when making a turn to port or starboard. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same, regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

Figure 2-3. Ship B - 80,000 DWT Tanker Maneuvering Characteristics

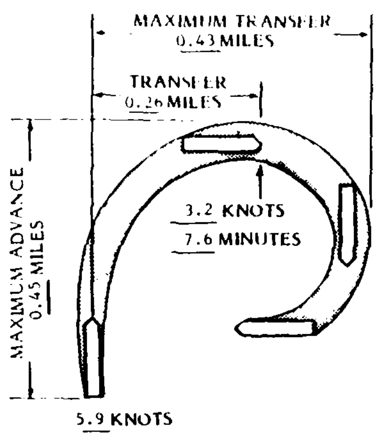
DEEP WATER MANEUVERING CHARACTERISTICS

CAORF LINES

S.S. EIGHTY KAY-C

Turning Circle Diagram

FULL LOAD / HALF SPEED



FINAL DIAMETER 0.30 MILES

DRAFT FWD 40' DRAFT AFT 40'

Length	763.0'	(232.6m)
Beam	125.0'	(38.1m)
Draft	40.0'	(12.2m)
Displacement	87142	TONS
Capacity	80000	DWT

Maximum Rudder Angle	STARBOARD RIGHT 35 DEGREES	PORT LEFT 35 DEGREES

TIME AND DISTANCE TO CRASH STOP		
	Full Load	
Engine Order	Time (Minutes)	Distance Miles
Full Sea Speed	19.5	2.26
Full Ahead	13.8	0.95
Half Ahead	10.5	0.51
Slow Ahead	4.0	0.11

ENGINE ORDER / R.P.M. / SPEED		
Engine Order	RPM	Speed (Knots) Full Load
Full Sea Speed	120	17.6
Full Ahead	60	8.8
Half Ahead	40	5.9
Slow Ahead	20	2.9
Dead Slow Ahead	10	1.5
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	40	
Full Astern	60	Time Full Ahead RPM to Full Astern 150SECS

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather - 10 knots or less, calm sea.
2. No current.
3. Water depth three times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less Advance.
2. There is no appreciable difference in the time or distance of ADVANCE and TRANSFER when making a turn to port or starboard. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same, regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

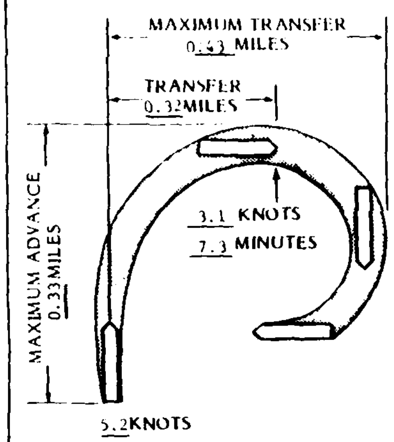
Figure 2-4. Ship C - 80,000 DWT Tanker Maneuvering Characteristics

DEEP WATER MANEUVERING CHARACTERISTICS

CAORF LINES S.S. EIGHTY KAY-E

Turning Circle Diagram

FULL LOAD / HALF SPEED



FINAL DIAMETER 0.31 MILES

DRAFT FWD 40'   DRAFT AFT 40'

Length	763.0'	(232.6m)
Beam	125.0'	(38.1m)
Draft	40.0'	(12.2m)
Displacement	87142	TONS
Capacity	80000	DWT

Maximum Rudder Angle	STARBOARD *RIGHT* 35 DEGREES	PORT LEFT 35 DEGREES

TIME AND DISTANCE TO CRASH STOP		
Engine Order	**Full Load**	
	Time (Minutes)	**Distance Miles**
Full Sea Speed	12.3	1.31
Full Ahead	8.7	.55
Half Ahead	6.2	.28
Slow Ahead	3.8	.10

ENGINE ORDER / R.P.M. / SPEED		
Engine Order	**RPM**	**Speed (Knots) Full Load**
Full Sea Speed	120	15.7
Full Ahead	60	7.9
Half Ahead	40	5.2
Slow Ahead	20	2.6
Dead Slow Ahead	10	1.3
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	40	
Full Astern	60	**Time Full Ahead RPM to Full Astern** 150SECS

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather - 10 knots or less, calm sea.
2. No current.
3. Water depth three times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less Advance.
2. There is no appreciable difference in the time or distance of ADVANCE and TRANSFER when making a turn to port or starboard. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same, regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

Figure 2-5. Ship E - 80,000 DWT Tanker Maneuvering Characteristics

The pilots were drawn from several pilots' organizations on the East Coast of the United States, four were members of the Sandy Hook Pilot Association, nine from the Boston Pilot group, one from Delaware, and two from the St. Lawrence Seaway area. The vast majority of the pilots had been to CAORF for previous experiments although, as indicated above, none had handled a ship in this scenario before.

Helmsmen for this experiment were drawn from the standard group that is used for all CAORF experiments. It should be noted that helm orders only were given as rudder commands by the pilots. This procedure had been used in the past to minimize the "helmsman effects" and to ensure that the control of the vessel is largely due to pilot performance. Therefore, the standard grouping of helmsmen used for most CAORF experiments was adequate for this latest experiment.

2.5 SCENARIO DESCRIPTION

All experiment runs were conducted in a waterway modeled after the "ABC" harbor described by the SNAME H-10 Panel on Controllability.

When entering a harbor certain specific maneuvers are of greatest concern. These maneuvers are track-keeping, track-changing, keeping and changing track while decelerating, and stopping. External conditions which most effect vessel control are water depth, water current speed and direction, wind speed and direction, and harbor constraints, such as channel width, turns, etc. The "ABC" harbor (Figure 2-6) includes a channel entrance with a cross-shear current, an S-turn consisting of two successive 25 degree turns, and a final right angle turn before an approach to an anchorage. Thus, it presents a series of realistic and representative requirements that a pilot/vessel might face on entering or leaving a port. Furthermore, it includes all of the important maneuvers cited above.

The wind, which was basically on the starboard beam for the major portion of the transit, tended to cause a starboard turning moment for all vessels. During the final leg, it became a head wind and tended to turn the vessel also when (depending on the vessel's crab angle) it fell on the starboard or port bow. Since the pilots' scenario directions were to slow down to 2 knots, this wind then tended to have a large effect on the ship's alignment with the desired track line as the ship's speed approached two to three knots. The current at the entrance of the channel caused a hard shear to port which, in turn, required close attention by the pilot. In addition, with the following current within the channel, any skewing of the ship with respect to the center line of the channel added a turning moment. The combination of the previously noted head wind *and* a following current, as the ships slowed in the last leg, caused a situation which also required constant pilot attention. It is obvious that the geometry of the channel, along with environmental conditions that were imposed, resulted in a transit which would effectively challenge most pilots' ability to maintain control of their vessels, therefore making the effects of variability in maneuvering characteristics more discernable than, say, in a simple straightforward passage.

Prior to the first familiarization run, each test subject was shown the chart of the harbor and a data sheet (Table 2-3) providing descriptive data on their ship's starting point, wind, current, channel dimensions and

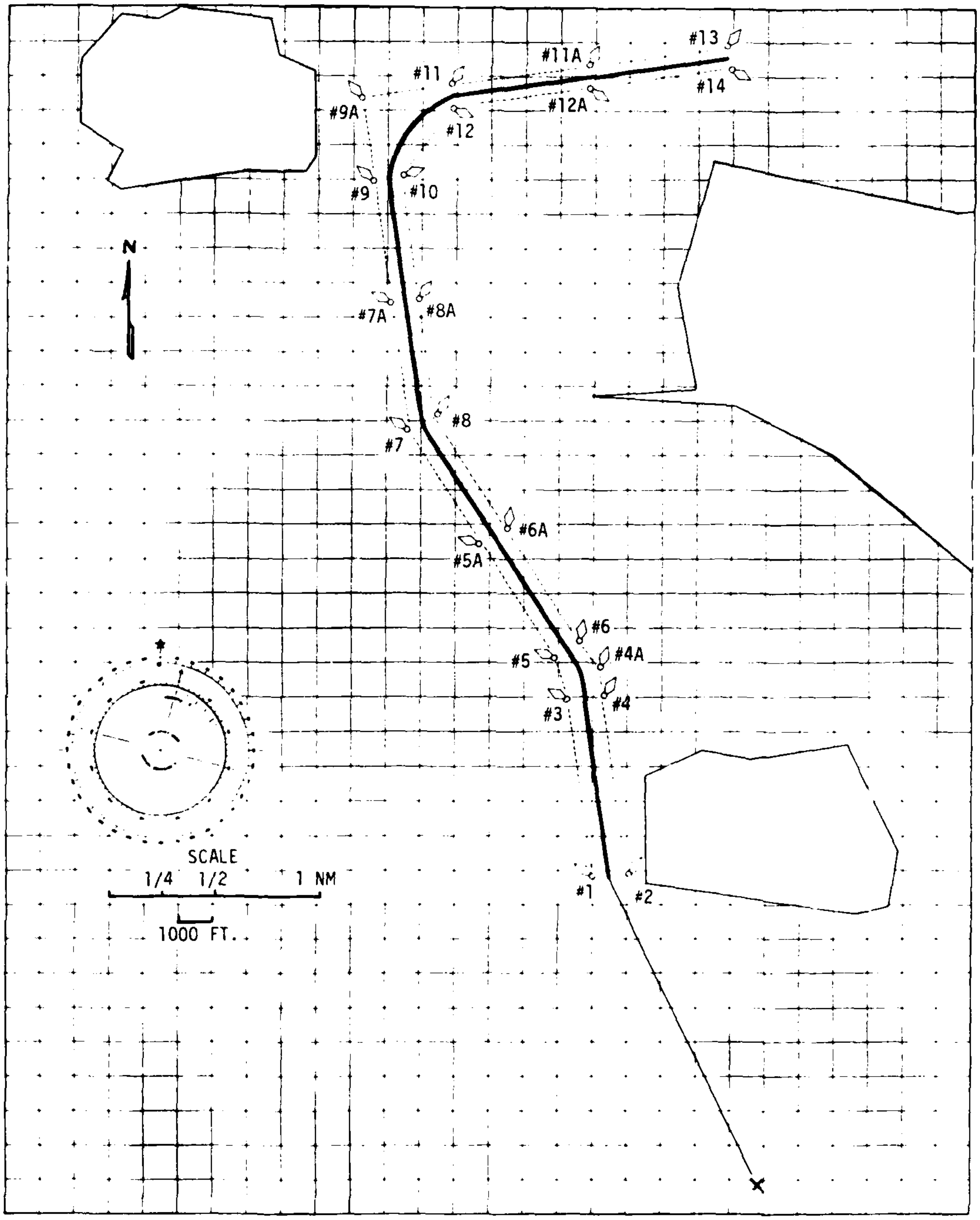


Figure 2-6. Chart of ABC Harbor

TABLE 2-3. CHANNEL INFORMATION SHEET

Ship starting point Approx. .09nm from channel entrance
Latitude - 34° 0' 26" N
Longitude - 119° 55'10" W
Heading - 333°
Starting at full ahead, 60 rpm, maneuvering speed

Wind 25 knot average ± 10 knots, from: 73° - 78°

Cross shear current 2 knots - 252°

Leg 1 352°
1000' wide
2000 yards long
1 kt current - 352° Flood

Leg 2 327°
800' wide
2850 yards long
1 kt current - 327° Flood

Leg 3 352°
800' wide
2400 yards long
1 kt current "Transition"

Leg 4 82°
600' wide
2700 yards long
1 kt current - 82° Flood

course lines. Subjects were told that for all runs the wind and current conditions in the harbor channel would not vary from those described, visibility would always be five miles, and no traffic would be encountered.

At the start of each experiment run, the subject's ship was underway at full-ahead (60 RPM) maneuvering speed. Subjects were instructed that they were free to vary engine speed as they saw fit, but that they were required to maintain a speed less than seven knots over the ground within the channel and to slow their ship to a speed of two knots over the ground as they came abeam of the final two buoys (13 and 14). It was also pointed out that if they deemed it necessary they might call up sea speed or even put the engines astern.

Prior to making any runs through the harbor, it was emphasized to each test subject that every effort should be made to follow a trackline in the center of the channel throughout each of their transits of the "ABC" harbor, including entering the harbor as close to the centerline as possible. The requirement to follow a centerline track applied to the straight segments of the harbor. In the turns, subjects were advised to follow the trackline shown on the harbor chart. This track had been derived from a data base of transits through the harbor which had been amassed from prior experiments. The directives regarding the trackline that subjects should attempt to follow produced a common basis for performance evaluation at the project's conclusion.

2.6 PROCEDURES

The simulator runs for this experiment were spread over a four month time frame. Rigorous and consistent control had to be maintained over the complete period to ensure that spurious confounding experimental effects due to differences in the procedural handling of the test subjects were minimized. A sequential listing of test subject activities was used for this purpose and is presented as Figure 2-7. The procedures follow a pattern of familiarization, experiment runs, interrun debriefings and final debriefing. In addition, the control station operators had a listing of items to be checked which would ensure that all run conditions and data collection were consistent. This is also part of Figure 2-7.

2.6.1 Test Subject Familiarization

As indicated above, some of the test subjects arriving at CAORF for this experiment were not familiar with the facility and, therefore, needed a complete familiarization. These test subjects initially viewed the indoctrination movie in the lounge area where they also attended to the necessary administrative details (expense account/T.S., P.O., etc.). A research staff member then discussed various relevent items with the test subjects, such as the relationship of CAORF to NMRC to MarAd to GDS and Sperry, the CAORF research program, the types of research which have been run in the past, test subject ID numbers for anonymity purposes, as well as the form and usage of research results. The fact that the work that they would be involved in at CAORF is neither training nor a testing process was emphasized. The test subjects' schedule at CAORF was also described.

As an aid towards familiarization, these test subjects were given the CAORF orientation manuscript to read, see Figure 2-8.

The general CAORF familiarization was then brought into more detailed focus for all the test subjects with an explanation of the simulator's ability to project the characteristics of different vessels. The first ship to be handled by each of the test subjects, the 30,000 DWT tanker was described as well as the availability of an experienced helmsman and the need for rudder orders rather than course orders. It was also explained that the purpose of the study was to investigate the variations in transit outcome that might result with ships of differing inherent maneuverability characteristics. A more detailed discussion (i.e., during final debriefing) of the objectives was delayed until completion of all runs.

The test subjects were told that they would be conning a 30,000 DWT tanker through the scenario for the purpose of becoming familiar with the channel conditions. They were to make two runs on this vessel and were shown the appropriate Deep Water Maneuvering Chart. It was also indicated that the ship had a bridge amidship. The conditions for the initial runs, and for that matter for all runs, would be clear visibility with no traffic. It was also indicated that the "data" runs would follow the two familiarization runs and they would be sailing on 80,000 DWT tankers for these following runs. All of these larger tankers would have the same geometric dimensions but would handle differently, one from the other. The location of the stern wheelhouse for all of the 80,000 DWT tankers was also mentioned as well as the fact that the appropriate Deep Water Maneuvering Characteristics would be available on the bridge prior to each of the runs.

MANEUVERING RESPONSE EXPERIMENT

Experiment Responsibilities and Sequential Schedule Check List for Pairs of Test Subjects

1. Test subject #1 will be greeted by the Test Subject Coordinator and will fill out necessary forms in the lounge area including a Test Subject Experience-Run Sheet form.

2. General familiarization regarding CAORF and current experiments by CAORF Research staff. The pilot will read CAORF orientation sheets, watch the movie and have the interrelationships of MarAd, NMRC, CAORF and GDS/Sperry explained to him. Use of ID numbers (anonymity) and the test subject schedule will also be covered.

3. The CAORF Research staff person will then brief the subject on the channel, starting position, desired track, current, wind, starting speed of full ahead maneuvering speed; i.e., 60 RPM. The harbor information sheet and chart will be used for this purpose. The subject is to be advised that he is to issue only rudder commands to the helm; no course commands, no "steady" commands. The pilot will also be advised of clear visibility conditions and that no traffic will be encountered in the channel. Subjects will also be instructed that they are free to vary speed as they see fit but that the Coast Guard regulations for the "ABC" harbor restricts this maximum speed to a 7 knot (over the ground) limit. They are required to slow their ship to a speed of 2 knots as they come abeam of the final two buoys (13 and 14) in the channel. It will also be pointed out that if they deem it necessary they may vary engine speed, call up sea speed or even put the engines astern. Location of the midship bridge on the 30,000 DWT tanker and the stern wheel house for all 80,000 DWT tankers will also be indicated.

   Prior to making any runs through the harbor it will be emphasized to each test subject that every effort should be made to follow a trackline in the center of the channel throughout each of their transits of the "ABC" harbor, including entering the harbor as close to the centerline as possible.

   The requirement to follow a centerline track will apply only to the straight segments of the harbor. In the turns, subjects will be advised to follow a trackline shown on the harbor chart. The pilots will be informed that a mate will be on the bridge keeping a log of engine and helm orders.

Figure 2-7. Experiment Responsibilities and Sequential Schedule Check List for pairs of Test Subjects

4. The mate will check that proper vessel characteristics booklet (#1) is on bridge.

5. Bridge equipment familiarization will be conducted by the Principal Investigator. Control Station staff/mate will then remain on the bridge during the channel familiarization, two runs. Bridge data sheets are not required for these two initial runs.

6. Two experiment runs will follow the familiarization runs. For each run the mate will note time and helm and speed orders on data sheets. The mate will also assure that portable mike is used for taping purposes.

7. Inter-run debriefing will be conducted after each run by CAORF Research staff personnel (PI).

8. Steps 1 through 7 for second test subject.

9. Steps 6 and 7 for runs 5 and 6 for test subject #1.

10. Final debriefing of test subject #1.

11. Steps 9 and 10 for test subject #2.

<u>NOTE:</u> Final debriefing of test subject 1 and run #5 for test subject 2 will occur concurrently. Also, the breaking of the activities after the second data run can be modified to accommodate the simulator scheduling.

12. The Control Station operators should be aware of the following for each run.
    - o The proper depth/current data base is loaded.
    - o Wind magnitude and direction has been set.
    - o Proper ship condition has been set, i.e., ship coefficients.
    - o Visibility is set at unlimited.
    - o Engine control is in the telegraph mode.
    - o Bow thrusters inoperative.
    - o Pre-Nav collection should be operative and saved.
    - o Video tape recorder should be set up.
    - o Gyro repeater and engine order telegraph are set prior to each run.
    - o The mate will have the responsibility during each run to record helm orders and engine orders.
    - o For <u>each</u> experiment run a Vessel Characteristics chart for the specific ship should be placed on the bridge.
    - o End of run criterion - 0 nm to go to way point between buoys 13 and 14.

Figure 2-7. Experiment Responsibilities and Sequential Schedule Check List for pairs of Test Subjects (Cont)

CAORF ORIENTATION

Welcome aboard the SS CAORF. We trust that your participation in the CAORF research program will be a stimulating and a rewarding one.

The purpose of this manuscript is to provide you with an orientation as to what CAORF is, including its objectives and capabilities. CAORF (Computer Aided Operations Research Facility) is the most sophisticated and versatile ship maneuvering simulator in the world today. It was developed by the U.S. Maritime Administration and is managed by the National Maritime Research Center.

A realistic shipboard environment is achieved in the CAORF simulator by means of a full-scale wheelhouse with a complement of actual bridge hardware that can be found on most large contemporary merchant vessels. The wheelhouse is 20 feet wide with a depth of 14 feet. The flexible design of the bridge provides the capability to vary equipment suite and physical arrangement, as desired.

The existing wheelhouse instrumentation consists of:

- Two relative motion/true motion radar sets with the simulator capability of generating and displaying up to 40 moving target ships and features normally found in the open sea, harbors, and docking areas, such as navigational aids and shoreline.
- A computer-aided collision avoidance system.
- Gyro pilot steering control stand which includes the helm unit, steering mode control, heading indicator, rate of turn indicator, rudder order and rudder angle indicators.
- Propulsion console consisting of combined engine order telegraph/throttle control, propulsion plant operating mode control, and RPM indicator.
- Bow and stern thruster controls, thruster output indicators and status lights.
- Speed log and ship's clock.
- Rate of turn indicator.
- Communications equipment including sound-powered telephone, ship's intercom system, single-side-band HF radio, VHF radio and ship's whistle.
- Wind speed and direction indicator.
- Loran radio navigation equipment.

Figure 2-8. CAORF Orientation Manuscript

One of the unique and more extraordinary features of the CAORF simulator is the computer-generated visual imagery projected using television techniques which simulates the scene of the outside world as seen through the wheelhouse windows. Around the bridge is a 60 foot diameter cylindrical projection screen onto which the external situation is displayed covering a 240-degree field of view in relative bearing and 24 degrees in elevation. Detailed presentations in full color can be provided of other ships, coastlines, buoys, bridges, buildings, piers and other significant elements of the visual environment. The scenario also includes "Ownship's forebody" which is superimposed on the centerline of the screen. The visual scene changes in real time in accurate response to own and other ship maneuvering motions. Other unique characteristics include the capability to (1) simulate restricted visibility conditions by altering the color intensity of an object in the visual scene as a function of the distance of the object from Ownship such that the color of the object approaches the color of fog or haze; (2) control the scene illumination level so that either day or nighttime scenes may be simulated; (3) vary the correspondence of the generated scene to the watchkeeper's eye height above the waterline for the particular Ownship being simulated; and (4) change the data base to simulate any port in the world; (5) change the data base to simulate many different vessels.

The conduct of experiments using the CAORF simulator is directed toward the achievement of the Maritime Administration's research goals, which are threefold.

- o To increase the productivity of the United States Merchant Fleet by minimizing delays and maximizing speed.
- o To recognize high risk areas and implement procedures and equipment to reduce these risks, thereby increasing productivity and cutting costs.
- o To reduce the cost of operations by developing new and safer procedures and equipment to minimize accidents and concurrent loss of life and damage to the environment.

Five major CAORF research programs have been planned which are directly tied to these goals and will be implemented over the next several years. They are in the areas of collision avoidance, ship control and navigation, bridge system design, and harbor and restricted waterway research as well as training and certification research. The objectives of these programs are to reduce the incidence of marine casualties and increase the capability of the watchkeeper to avoid collisions, to derive operational criteria and standards for the Maritime industry, and to develop merchant vessel and port design guidelines. It is with your cooperation and participate in the upcoming CAORF experiment that we hope to continue accomplishing these goals.

Figure 2-8. CAORF Orientation Manuscript (Cont)

The channel information sheet and chart was then discussed in detail. It was indicated that the water depth within the channel was quite deep (200'), but that the areas outside of the channel contained wrecks, obstacles, etc. This reasoning for staying within the channel was accepted by all pilots. It was indicated that the winds were primarily on the beam, except for the last leg, and that the current was "following" within the channel. The two knot shear current at the entrance was also emphasized. Speed conditions and restrictions were indicated; starting at 60 RPM maneuvering speed, reduction to seven knots or less within the channel and a reduction to two knots at the final two buoys #13 and #14. Within these restrictions the pilots were free to vary engine speed as they desired to maintain control of their ships.

The test subject and principal investigator then went to the bridge and all equipment including steering stand, radars, wind instruments, phones, speed telegraph and all remaining indicators and instrumentation were briefly discussed prior to the start of the familiarization runs. The data taker "mate" and helmsman were then left on the bridge with the test subject as the runs commenced.

2.6.2 Experiment Runs

At the completion of the second familiarization run the test subject was shown the new maneuvering chart information for the first data run and assured that all other conditions would be the same as in the familiarization runs. The run was then accomplished and the test subject was debriefed concerning his reactions to the ship used and interactive ship/channel factors. The debriefing form is shown as Figure 2-9. This procedure was repeated three additional times; discussion of the ship to be used, the run, the inter run debriefing. At the conclusion of the sixth run (the fourth data run), a final debriefing was held with each subject.

2.6.3 Final Debriefing

At the conclusion of the last run, a final debriefing was held with each test subject by a member of the CAORF research staff. This was taped on a small audio recorder and followed a structured format. Questions regarding the subjective reactions to the overall experiment, vessel handling, and actual experience under similar conditions by the pilot were explored. Figure 2-10 is a summary listing of questions.

2.7 DATA COLLECTION

A variety of sources were used for data collection during the running and analyses of the experiment. The major performance measures were obtained from computer summary datalogs, ship's bridge data sheets (Figure 2-11), precise navigational data printouts, and debriefings. The primary source for all objective data during the actual experiment runs was the "playback tapes." This is a magnetic recording of each run, taken at a fixed time interval, of important computer and ship parameters (numbering well over 1,000 items). The recording rate for the Maneuvering Response experiment was once every 10 seconds.

2.7.1 Computer Summary Datalogs

Computer-summary datalogs are printouts from the playback tapes. A small number of parameters were made available to research personnel monitoring the experimental runs.

INTER RUN DEBRIEFING SHEET

SUBJECT # ______________________________ RUN # ________________

INTERVIEWER ____________________________

1. Was the ship difficult to handle?

2. What handling characteristic(s) contributed to this evaluation?

3. Was there a particular area or areas of the channel that was/were difficult for this ship?

4. a) Was the ship realistic (in general)?

   b) In particular was there any unrealistic characteristic?

   c) Have you handled this type of ship before, in your home area?

5. On a scale of 1 to 5 - (5 being more difficult to handle) how would you rate the maneuvering characteristics of this vessel?

   1 2 3 4 5

Figure 2-9. Inter Run Debriefing Sheet

FINAL DEBRIEFING SHEET

SUBJECT # ______________________ RUN # ______________

P.I. ______________________

1. Based on your previous ranking of ship maneuvering characteristics, how would you rank (overall) the maneuvering difficulties that you experienced during your five runs. 1 being most difficult.

RANK	1	2	3	4	5
RUN					

2. Was the track line that we asked you to maintain the one that you would have selected, under no traffic condition? If not, what would you have selected?

3. Was the overall task realistic - How do the requirements of the channel compare with your home area?

4. We tried to vary the tasks in the channel to bring out differences in shiphandling capabilities required for the four ships. Do you think we could have added or changed anything to have made differences in inherent maneuvering characteristics more obvious? Are there any situations in your home area which present particularly difficult maneuvering problems?

5. I'm sure that you have gotten to recognize certain classes of ships as "dogs." Other than equipment or machinery failures, what characteristics, capabilities, or lack of capability, make one vessel more difficult to handle compared with another?

Figure 2-10. Final Debriefing Sheet

MANEUVERING RESPONSE EXPERIMENT DATA SHEET

ENGINE AND RUDDER ORDERS (SHIP #__________)

SUBJECT I.D. # ____________________ MATE ____________________

RUN # ____________________ HELMSMAN ____________________

PLAYBACK TAPE # ____________________ DATE ____________________

BRIDGE TIME	ENGINE ORDERS	RUDDER ORDERS

Figure 2-11. Maneuvering Response Experiment Data Sheet

These were called up on command at the Control Station Digital Display. This information was then available as hard copy printouts at the end of groups of runs. A listing of the items obtained on the printouts is shown in Table 2-4.

2.7.2 Precision Navigation Data Printouts

During the actual runs, stored parameters as well as specially computed parameters were made available to research personnel monitoring the experimental runs. These were called up on command at the Control Station Digital Display. This information was then available as hard copy printouts at the end of groups of runs. A listing of the items obtained on the prinouts is shown in Table 2-5.

2.7.3 Plots

At the conclusion of each run, a track plot was generated from the playback tape, which shows a plan view of ship's position for every two minutes of the run against a background of the"ABC" harbor channel. These plots are presented in Chapter 3, grouped by subject, and presented in Run Order sequence. They were used for assessment of Piloting Difficulty and analysis.

The statistical analyses of the experimental data were conducted with five of the six leg segments, legs 2 through 6, which include all three turns, i.e., the 25° turn to port, the 25° turn to starboard and the 90° starboard turn. The approach leg was not analyzed since it was a ship familiarization

TABLE 2-4. COMPUTER SUMMARY DATALOG PARAMETERS

1.	Bridge Time
2.	Ownship Ground Speed (knots)
3.	Ownship North Coordinate (nm)
4.	Ownship East Coordinate (nm)
5.	Ownship Heading (degrees)
6.	Ownship Yaw Rate (radians/sec)
7.	Rudder Angle (degrees)
8.	Engine Propeller Speed (rpm)
9.	Ownship Fore/Aft Speed (feet/sec)
10.	Ownship Athwart Speed (feet/sec)
11.	Water Depth (feet)
12.	Actual Wind Speed (knots)
13.	X Axis Rudder Force (lbs)
14.	Y Axis Rudder Force (lbs)
15.	Rudder Yaw Moment (lb-feet)

TABLE 2-5. PRECISION NAVIGATION DATA PARAMETERS

1.	Bridge Time
2.	Playback Tape Number
3.	Channel Leg Number
4.	Distance to Way Point (nm)
5.	Distance Off-Track (feet)
6.	Speed Along Track (knots)
7.	Speed Across Track (feet/minutes)
8.	Incremental Distance Along Track (feet)
9.	Crab Angle (degrees)
10.	Yaw Rate (degrees)
11.	Ownship Heading (degrees)
12.	Rel. Wind Speed/Ship Speed (knots/knots)
13.	Rel. Wind Angle (degrees)
14.	Rudder Angle (degrees)
15.	RPM (rev./min)

phase. Summary plots were made which contain these five segments to graphically demonstrate the trends caused by the primary experimental variable (ship maneuvering characteristics). At 1/8 NM points along these segments, the ship position of all 16 test subjects, for each ship, were averaged and displayed. In addition, the maximum and minimum value off-track at each 1/8 NM were also shown as well as plus and minus one standard deviation of each sample. These plots were generated as functions of distance from the centerline desired track. The desired track is shown as a continuous straightened path; that is, a straight line with no breaks or curves. The four resultant summary plots (one for each vessel) are contained and discussed in Chapter 3 of this report.

CHAPTER 3
RESULTS AND DISCUSSION

3.1 INTRODUCTION

The major purposes of the Maneuvering Response experiment were to determine both the variations in ship handling performance which are attributable to differences in vessel inherent maneuvering characteristics as well as the impact on pilots' workload caused by these differences, and to investigate the pilots' perception of the ship handling difficulties caused by the transit conditions and inherent maneuvering characteristics of the vessels. The experimental data have been subjected to a variety of analyses and the findings are presented and discussed within this chapter.

The basic question that this experiment has attempted to explore is concerned with a facet of "Pilot Lore." When asked about potential problems concerning the process by which they become familiar with vessels that they have not sailed before, experienced pilots commonly express the view that they can get the "feel" of a new ship very quickly after taking the conn. This "feel" implies the ability to handle the vessel safely throughout the pilotage area. The fact that this is accomplished in an efficient professional manner is evidenced by statistics related to the high level of safe passages that do occur every year under highly variable conditions. A question, therefore, exists regarding the variability of this familiarization ability and the manner in which different vessels and different pilots affect the man/ship performance which is displayed. To experimentally examine this question a task must be set, the controllability of the ship must be made variable and suitable measures must be established to allow judgements to be made regarding the question of whether or not differences in performance actually exist. This was done in the experiment reported herein.

The experimental task that was established for each of the test subjects was to transit the experiment's scenario on each of four vessels. The vessels were the same length, breadth, and displacement, but handled differently; not an unrealistic situation. The differences in inherent maneuvering characteristics of the ships were primarily due to differences in stability. Appendix B contains information regarding the stability of the four ships, ship A, B, C and E. The test scenario that was used was the ABC Harbor, consisting of an approach phase, three legs containing both a 25° port and 25° starboard turn, a 90° turn to starboard and a final leg. The scenario conditions were designed to be difficult enough to require the full attention and concentration of the pilots, yet remain realistic. By this means the sensitivity of the measures used to monitor performances was increased making ship and pilot variability more discernible. If the task was made too easy all pilots on all ships would perform in a virtually identical manner making it impossible to see differences, and if it were made too difficult the task would not only be unrealistic but none of the test subjects could be able to complete it successfully.

The pilots became familiar with the ABC Harbor by means of two preliminary runs on a 30,000 DWT tanker, a ship that was not used for the experimental runs. Once the harbor familiarization runs were completed the

test subjects were ready to begin actual data runs. They became familiar with each of the 80,000 DWT tankers (the ships used during the data

runs) during the 1.6 nm approach phase of each run. The approach phase was therefore used primarily for ship familiarization purposes and did not enter into the ship performance evaluation.

Several environmental conditions and restrictions made the transit somewhat taxing. The entrance 2 knot shear current had to be mastered. The mild 25° starboard turn tended to combine with the starboard beam wind effects on stern wheel-house vessels causing a tendency to make leeway to the port side of the channel. If the vessel crabbed excessively then the following current also tended to increase the starboard turn rate. All of these conditions were combined with the 7 knot speed restriction, requiring close attention on the part of the pilot. Wind, current and the starboard 90° turn also combined to present a compelling task for the mariner. This latter portion of the channel was quickly followed with the conditions of the last leg; a following current, a head wind and a need to slow to 2 knots. If the ship attained any angle with respect to the desired course line, these conditions combined to make recovery somewhat difficult.

The experimental results show that the ship, scenario and environmental condition truly tested/taxed the pilots' capabilities. Many passages were uneventful, some showed more difficult transits in certain key areas, and in a small number of instances it was apparent that control was lost for a period of time. By these techniques which have been described, it was possible to note clearly defined differences and variability in pilot/ship performance, as had been planned.

Paragraph 3.2 contains the results of the statistical analyses (ANOVA). These analyses make use of multiple performance measures to define performance differences which had been demonstrated under the range of ship stability criteria which was examined. The majority of these analyses was based on channel leg comparisons as well as overall channel transit performances, exclusive of the channel approach area. Additional analyses were performed on the experimental data by making use of individual ground track plots in the examination of the key areas of the scenario which had caused the most difficulty for the pilots. These latter findings are presented in Paragraph 3.2.2.

Summary ground tracks are presented and discussed in Paragraph 3.3. The ground tracks that are shown have been generated from performance data which have been averaged for each ship. The plots indicate the nature of the average tracks as well as the variability of the tracks within the five key legs of the scenario. These tracks are presented for each of the four ships that were used in the experiment.

The sixteen pilots used for this experiment comprise a randomly selected sample of pilots experienced with vessels which are similar to those used in the experiment. This grouping of pilots was derived from a so-called parent population of all pilots experienced with these vessels.

By using standard analytical techniques, estimates of this population's distribution of various performance measures can be derived from the sample group statistics. These findings therefore define the probable performance distribution of the parent population. The confidence interval of the population means as well as probable range of standard deviations

were developed for several primary performance measures used in this experiment. These findings are presented in Paragraph 3.4.

Insights into the test subjects' reactions to the experimental task, vessels, scenarios, etc. were collated from debriefings which had been held with each pilot after completion of their runs. These results are summarized in Paragraph 3.5.

3.2 STATISTICAL ANALYSES OF PERFORMANCE MEASURES

The Maneuvering Response experiment was structured so that the experimental data were capable of being analyzed from two viewpoints. The first is based on differences in inherent ship maneuvering capabilities. The second approach is based on an experience factor; that is, the order in which the channel transits were accomplished. The primary purpose of the statistical analyses was to determine if differences existed in the performance exhibited by the sample group of experienced pilots as they transited the "ABC" Harbor under various controlled conditions.

Performance was evaluated by means of a set of measures which were concerned with both pilot actions (pilot performance measures) and with the results of the actions (system performance measures). The performance comparisons were made between pilotage exhibited within the channel (legs 2 through 6) since the approach to the channel, leg 1, was used as a ship familiarization phase. Two types of comparisons were made, dependent on the measure; one was based on differences between ships and channel legs, and the second was based essentially on total channel performances in legs 2 through 6. The majority of the findings from the total channel performance analyses were similar to the analysis based on a ship and leg separation and will be reported as part of the findings for each performance measure. There were also measures that were used which occurred only once per run, such as ship speed at the end of run or ship center of gravity distance off the entrance buoy (#1) at closest point of approach (CPA).

The conditions that were designed into the different channel legs were established to present a variable pilotage challenge so that differences in ship characteristics would become more evident. It is therefore not surprising that all observed measures showed a main effect for the leg variable. The principal areas of interest which will be discussed within this section are those statistical results which indicate a main "ship" effect in the statistical comparisons or more importantly an interaction effect between ships and legs. Main "run order" effects and run order and leg interactions will also be noted. Appendix C contains the results of all ANOVAs and post hoc comparisons that were accomplished for this experiment.

3.2.1 System Performance Measures

The primary system performance measures that were used for the statistical comparisons were functions of off-track deviation (X) including X_{RMS}, $X_{AVERAGE}$ ($\bar{X}$), and standard deviation of X (X_σ). Swept path (S.P.) and penetrations of the channel boundary limits (BP) were also used. In addition several functions of ship's speed over the ground (VOS) were evaluated since the pilots had been told to control their speeds, i.e., limit speed to a maximum of 7 knots through the channel and then to slow to 2 knots in the final leg.

3.2.1.1 Root Mean Square of Off-Track Deviation, X_{RMS}

Significant differences were found for the measure of X_{RMS} for the pilots' performance on the different ships in the different legs. As shown in Figure 3-1, (as well as Appendix C), these differences occurred primarily on Ship A compared with the other vessels in leg 4, the 90° turn and leg 6. The X_{RMS} for leg 4 - Ship A was significantly largest at 188 feet while for the other ships values of 129 feet (B), 107 feet (C), and 74 feet (E) were found. In the 90° turn Ship A showed 211 feet while the other ships were significantly lower, 99 feet (B), 119 feet (C) and 119 feet (E). In the final leg (#6), Ship A was 143 feet while the other vessels were 68 feet or less. Ship differences in the other legs were not statistically significant.

Based on this measure it would appear that when pilots transited on Ship A they had more difficulty conning their vessels under two conditions; when they made small or large standard turns with starboard winds (leg 4 and 5), and when they had head winds, a following current, and were required to slow their vessel (leg 6).

The overall performance for the total channel (legs 2 through 6) are shown in Figure 3-2 and indicate similar findings. Overall, pilots conning Ship A found that they had more difficulty on that unstable vessel than on the other three more stable ships.

3.2.1.2 Standard Deviation of Off-Track Deviation, X_{σ} (Consistency)

Consistency of off-track deviation is another figure of merit of the level of difficulty that the pilots exhibited while transiting the channel. It is a function of the variation in actual track line measured in feet around the mean track line during each transit, i.e., standard deviation or X_{σ}. A larger variation around the mean track line would normally be attributed to a higher level of difficulty encountered in the controllability of the vessel, since a vessel that is well controlled would not "wander" about its mean track line as much as one on which the pilot was experiencing greater difficulty.

Significant differences were found between Ship A and the other vessels for four of the five legs examined. There were also differences in leg 4 and 6 when the pilots conned Ship B compared to their actions on Ship E. These findings are shown in Figure 3-3 (and Appendix C) and demonstrate again that the pilots had more difficulty controlling the unstable vessel (A) than the more stable ship designs. Ship B is somewhat more stable than A, and performance on Ship B was shown to be significantly different (poorer) than on the stable ship (E), in leg 4 and leg 6 as noted above. These findings show a significant trend in consistency of performance based on stability in those legs which have more difficult pilotage problems. Figure 3-4 presents the total channel findings for consistency and again indicates a wider divergence from average track with Ship A compared to the other vessels.

3.2.1.3 Average Value of Off-Track Deviation, $\bar{X}$

$\bar{X}$ is a performance measure which takes the direction of distance from the center track line into account, positive is to starboard and negative is to port. The magnitude of $\bar{X}$ is therefore normally smaller than X_{RMS} and is only equal to X_{RMS} when X_{σ}, the standard deviation, is equal to zero.

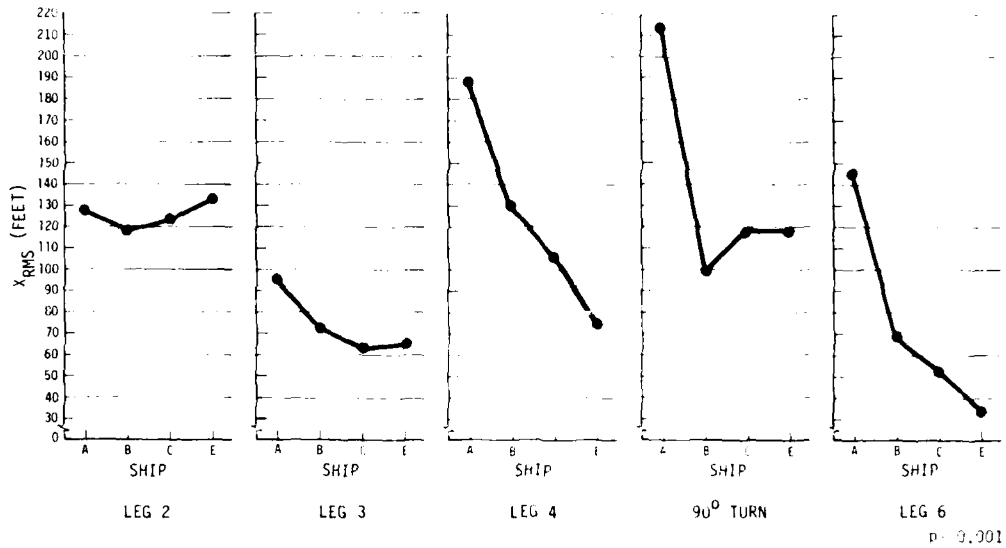


Figure 3-1. Ship Effect Comparison - X_{RMS} By Leg

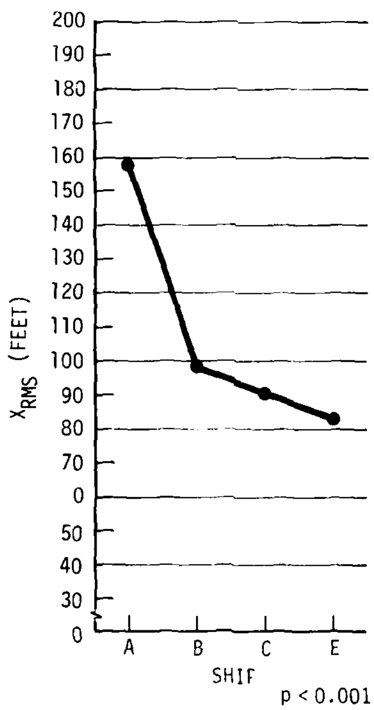


Figure 3-2. Ship Effect Comparison -X_{RMS} - Total Channel

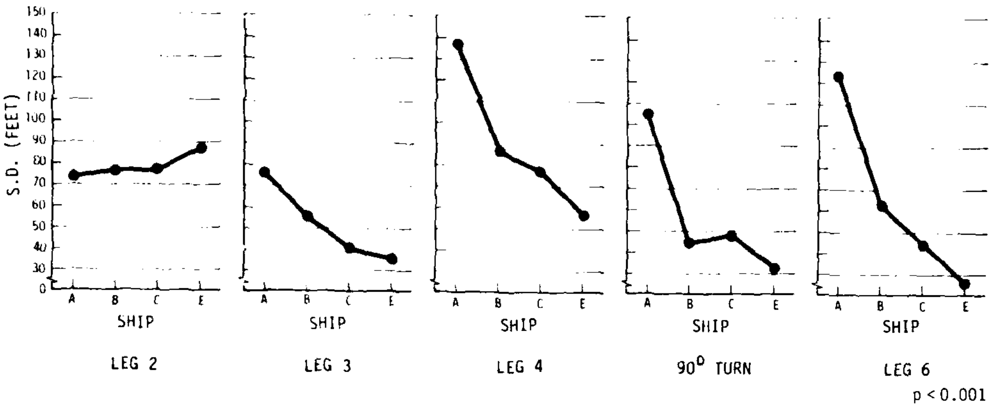


Figure 3-3. Ship Effect Comparison - Consistency (S.D.) By Leg

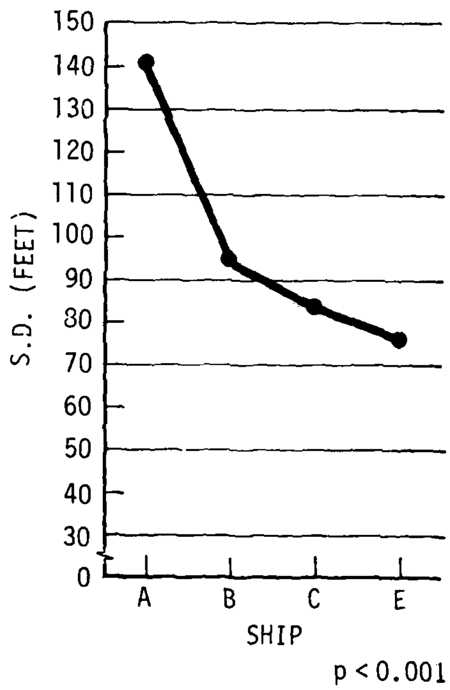


Figure 3-4. Ship Effect Comparison - Consistency (S.D.) -Total Channel

The ANOVA comparisons for this measure are plotted in Figure 3-5 and the 90° turn reflects the largest significant differences between performance on the different ships. Performance on Ship A averaged 181 feet to the left, Ship B and Ship C approximately 10 feet to the left, and Ship E 97 feet to the right. The value for Ship A was significantly different than for Ships B, C, and E. In addition, Ship E was significantly different compared with Ships A, B, and C. In this leg, the differences in ship handling characteristics are most striking and are underscored once again by the ships at the stability extremes, i.e., Ship A and Ship E. The 90° turn with Ship A was wide while control on Ship E was greater, allowing the pilots on average to stay on the inside of the turn with the latter vessel.

In leg 4 the $\bar{X}$ for Ship A was -109 feet, Ship B was -83 feet, Ship C was -45 feet and Ship E -12 feet. The stable Ship E differed significantly in comparison with Ship A and Ship B, that is, a smaller average off-track deviation on the more stable ships compared with the less stable ships.

The total channel findings are indicated in Figure 3-6 with $\bar{X}$ performance on Ship A indicated as significantly larger (to the left of center channel) than on the other vessels.

3.2.1.4 Swept Path (SP)

The swept path exhibited by the four vessels showed significant differences in all legs except leg 2. In leg 3 control on Ship A (as measured by SP) was poorer than on Ships C and E. This can be seen in the SP findings illustrated in Figure 3-7. In legs 4 and the 90° turn, all ships differ significantly from one another with the least stable vessel having the largest SP and the most stable the smallest.

In the last leg the average SP when Ship A was being conned (199 feet) was significantly larger than for Ship B (164 feet), Ship C (153 feet), and Ship E (147 feet). It should again be noted that the minimum value of SP is the ship beam width, 125 feet. Comparison tests also indicated that the value of SP for Ship B was significantly larger than for Ship E in the final leg.

This system performance measure of SP has therefore also shown that the pilots had more difficulty with control of these vessels when they were transiting the channel on the less stable ship than when they were on the other more stable vessels. This is also underscored by the total channel findings, Figure 3-8.

3.2.1.5 Boundary Penetrations (BP)

Perhaps the most realistic measure for evaluation of differences in ship performance would be the number of times that the skin of the conned vessel penetrated the channel boundary. This is most directly related to pilotage safety and its reduction is therefore the essence and desired end-all of pilot experience and training. Figure 3-9 contains the findings for this important measure and illustrates that leg 4, the large 90° turn, as well as leg 6 again caused the most problems for the pilots. A significantly larger average BP was experienced on Ship A in those legs compared with the other vessels. The average BP was obtained for each ship by taking the number of penetrations that occurred on a vessel and averaging it over the number of subjects in each grouping (i.e., 16). It is apparent from Figure 3-9, and as also discussed in Section 3.2.4, that the pilots tended to have extreme difficulties with the control of the unstable ship (A),

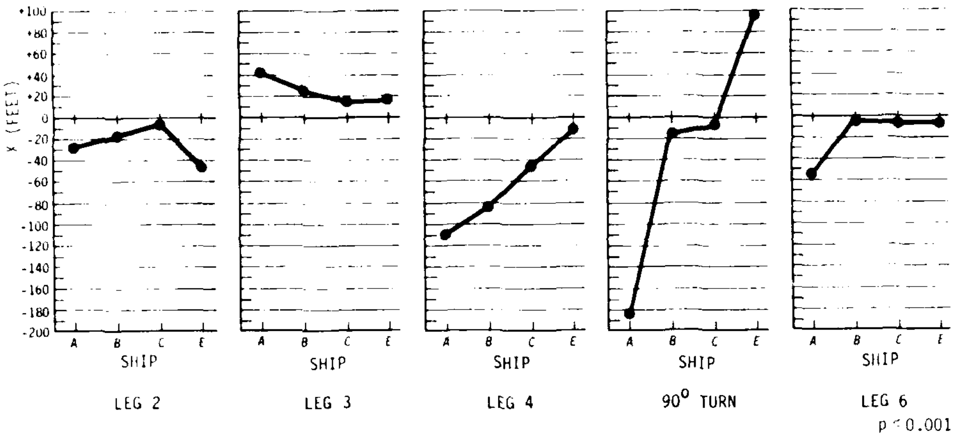


Figure 3-5. Ship Effect Comparison - $\bar{X}$ By Leg

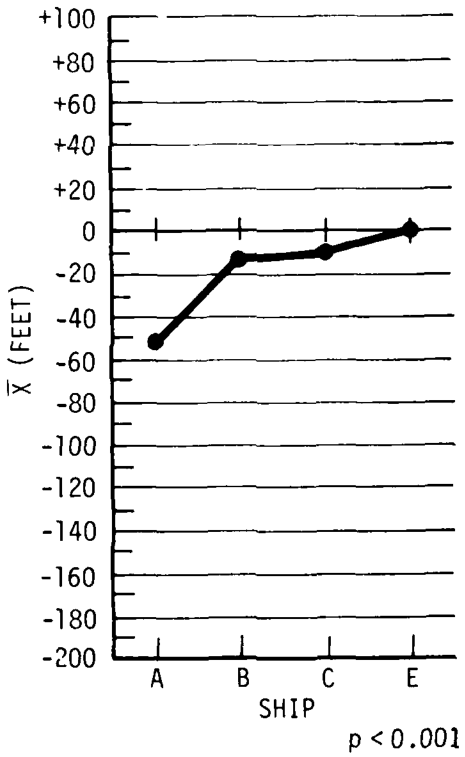


Figure 3-6. Ship Effect Comparison - $\bar{X}$ - Total Channel

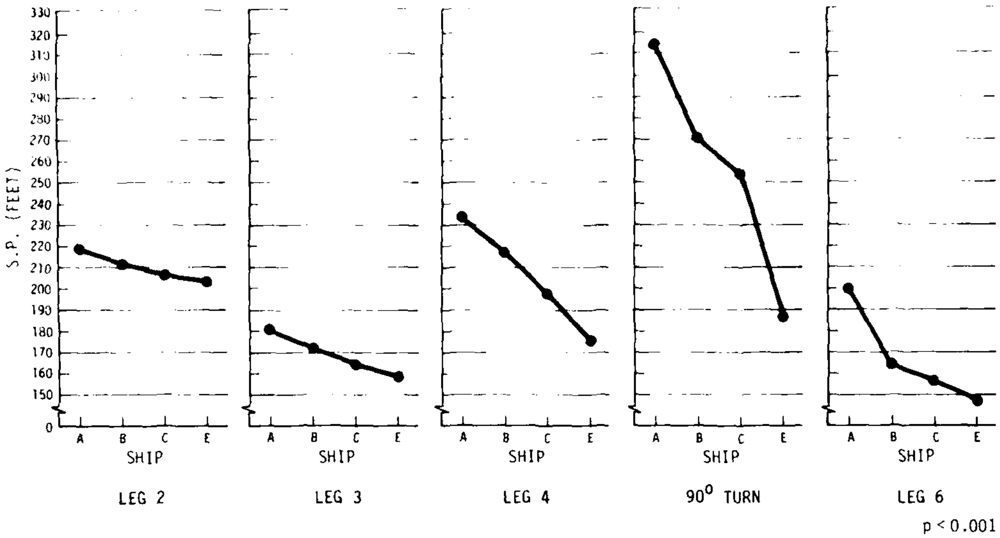


Figure 3-7. Ship Effect Comparison - Swept Path By Leg

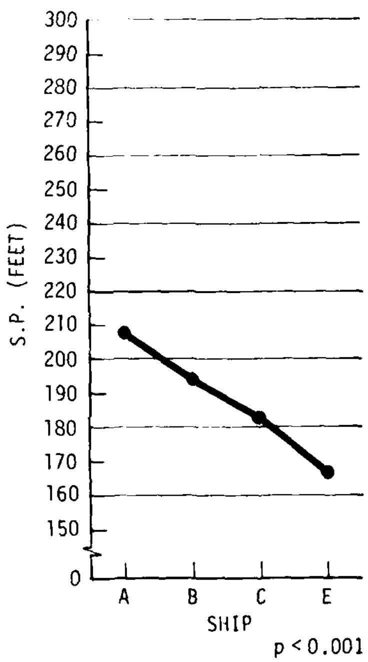


Figure 3-8. Ship Effect Comparison - Swepth Path - Total Channel

especially when the following current, wind and starboard turns caused the ship to "side slip" out of the channel. Figure 3-10 indicates the overall channel results and shows the significantly larger average Boundary Penetrations experienced by the pilots on Ship A.

Because of the safety implications, it should be especially emphasized that these findings, as with all ship-effect findings, are without reference to the order in which the pilots made their runs. Experience with the simulator and/or channel was *not* a factor in this regard.

3.2.1.6 VOS and Percentage of Time Speed Over 7 Knots

The pilots were instructed that ship speed over the ground on all vessels was to be maintained under 7 knots throughout the channel and reduced to 2 knots by the end of leg 6.

Average speeds in different legs therefore reflect the general difficulties that existed for the pilots and in turn comparisons between the ship average velocities were indicative of the pilots' needs on different vessels to increase speed to maintain control under the conditions that were presented to them. Figures 3-11 and 3-12 contain the findings for average speed (VOS) and Figures 3-13 and 3-14 are for the average percentage of time the speed was over 7 knots.

Figure 3-11 indicates the general trend of decreasing velocity as the ships traversed the channel, e.g., for Ship A the VOS in knots was 9.3, 7.8, 6.9, 5.4 and 4.4 for legs 2, 3, 4, 90^{o} turn, 6 respectively. The average velocity for Ship A was significantly larger than Ship B and E in leg 2, Ship E in leg 3, and all other ships in legs 4 and 6. Ship E was significantly smaller than Ships B and C in leg 2. Overall, the speed on Ship A was significantly larger than on the other vessels (Figure 3-12).

Figure 3-13 indicates that the speed on vessel E was greater than 7 knots for a significantly smaller percentage of time in leg 2 than on any of the other vessels. In leg 2 the value of this measure for Ship A was larger than for Ship E, Ship B was larger than Ship C, and Ship C was larger than Ship E. In leg 4 the percentage of time the speed was greater than 7 knots on Ship A was significantly larger than for any of the other ships.

These ship speed findings tend to mirror the results of the other comparisons which have previously been presented. When control difficulties caused pilotage problems, the pilots took the most severe actions (larger speed) on Ship A. Additionally, when differences in speed were found it was most often Ship E which allowed the smaller speed to be maintained because of greater inherent control.

3.2.2 Pilot Performance Measures

Frequency of rudder commands as well as frequency of rudder commands plus engine commands were selected as measures for assessment of pilot workload, i.e., the effect that the pilotage difficulties had on the pilot himself. Figure 3-15 illustrates the findings of the rudder command (R_T) comparisons which were made. No significant findings occurred with the rudder plus engine command measure comparison between ships. However, a significant difference for average rudder plus engine commands was found between legs as shown in Figure 3-16.

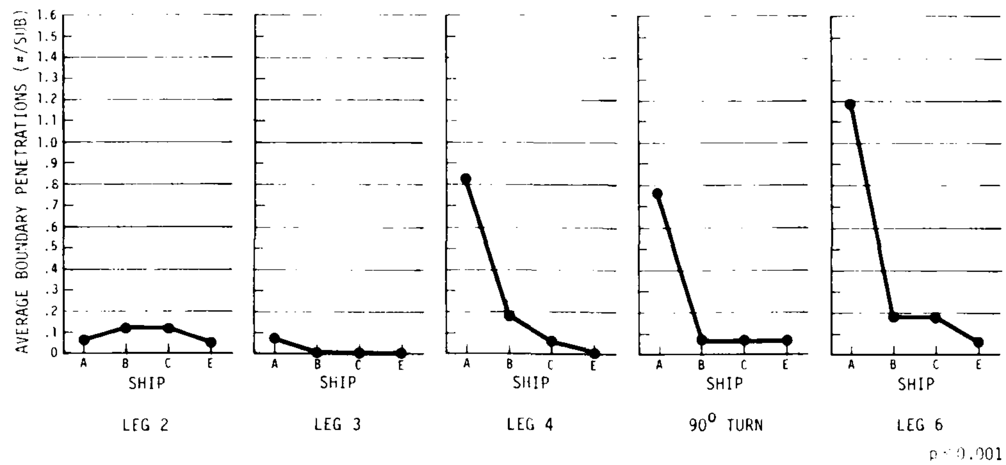


Figure 3-9. Ship Effect Comparison - Average Boundary Penetrations By Leg

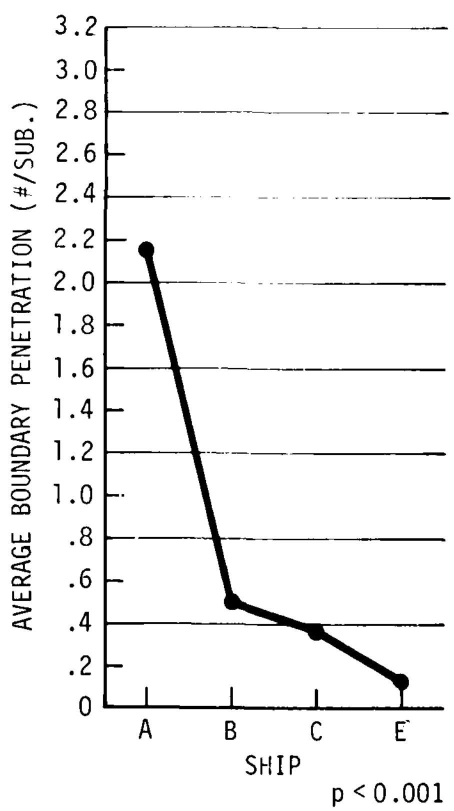


Figure 3-10. Ship Effect Comparison - Average Boundary Penetrations - Total Channel

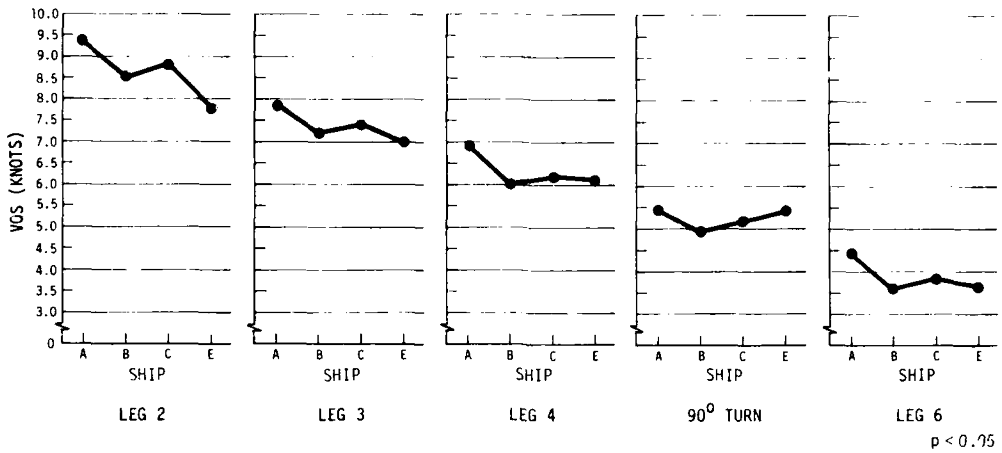


Figure 3-11. Ship Effect Comparison - VOS By Leg

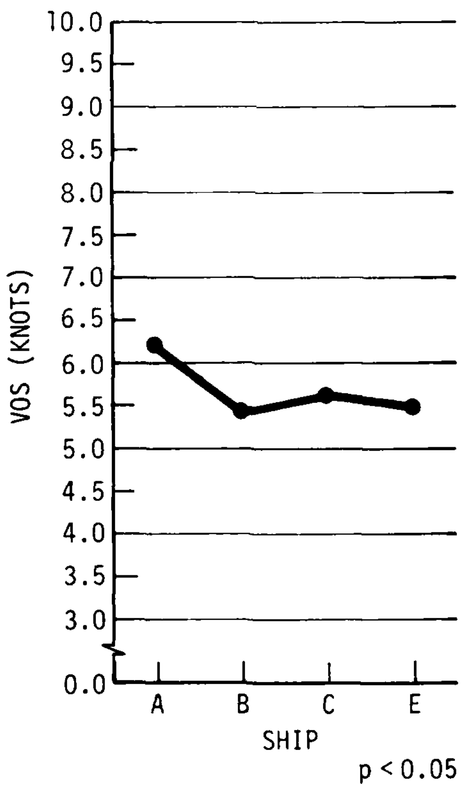


Figure 3-12. Ship Effect Comparison - VOS - Total Channel

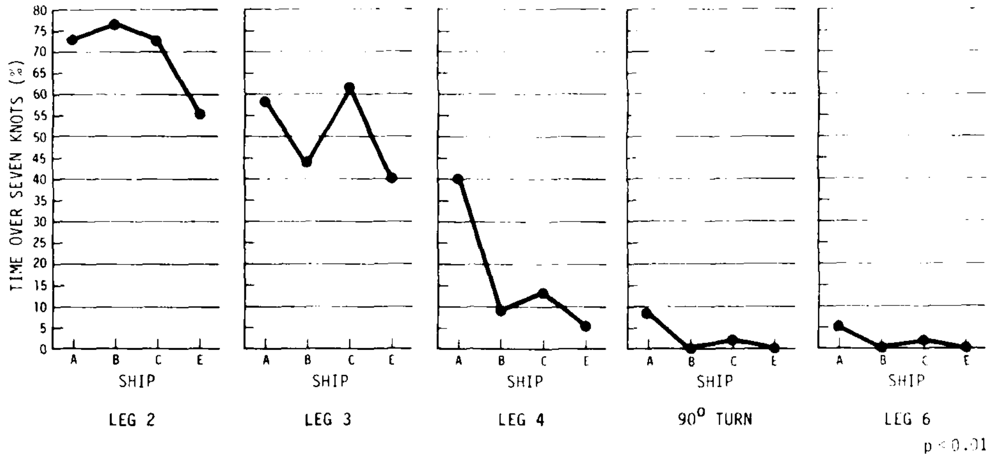


Figure 3-13. Ship Effect Comparison - Percentage of Time Over Seven Knots By Leg

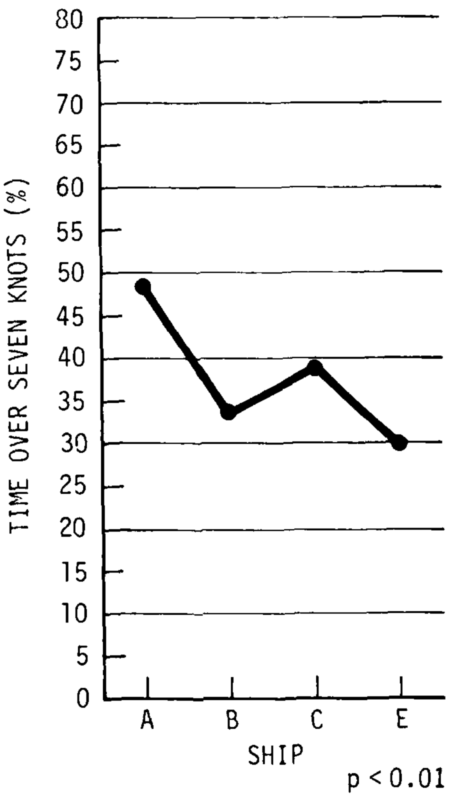


Figure 3-14. Ship Effect Comparison - Percentage of Time Over Seven Knots - Total Channel

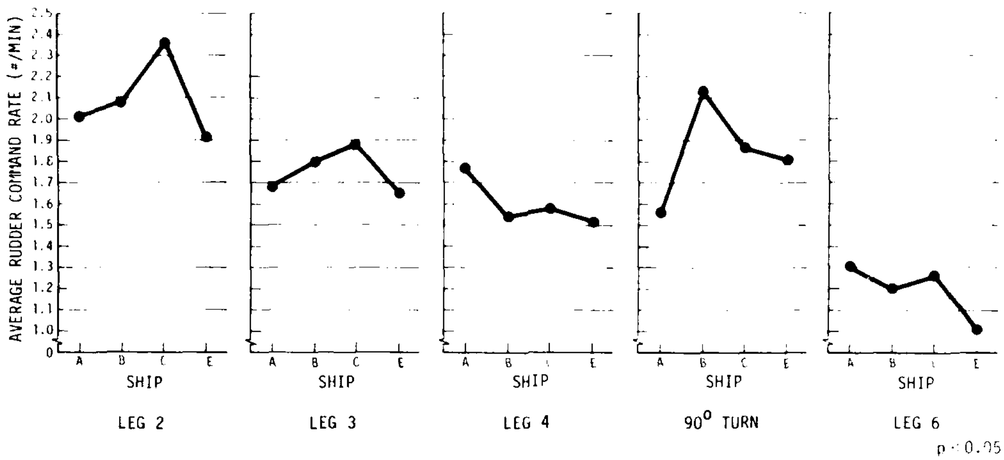


Figure 3-15. Ship Effect Comparison - Average Rudder Command Rate By Leg

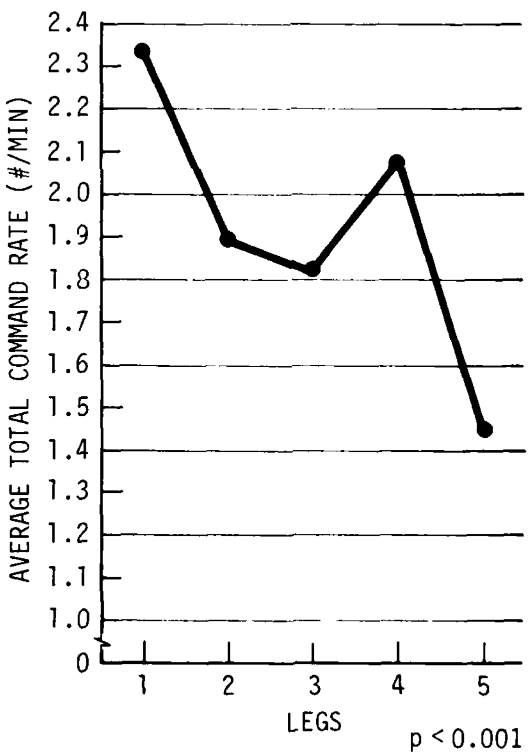


Figure 3-16. Leg Comparison - Total Command Rate

Figure 3-15 indicates that the number of commands/minutes that the pilots used on Ship E was significantly lower than on Ship C in leg 2. In the 90° turn, the frequency of rudder commands issued on Ship B was significantly larger than on any other vessel.

The level of significance that resulted from the ship comparisons performed for this measure was found to be $p < 0.05$, which is actually the smallest level that has been established as still reportable for this experiment. It would appear from these analyses concerning the effects of the channel difficulties on the pilots' workload that one of two possibilities exist; i.e., the effect is minor if any, or the performance measures selected and used were inadequate to demonstrate the effects.

3.2.3 Run-Order Effects

The previous findings of Paragraphs 3.2.1 and 3.2.2 were based on comparisons between performance demonstrated by the pilots on the four ships that were used in the experiment to discern whether or not the conditions in the passage caused differences, which could in turn be attributed to the inherent maneuvering characteristics of the vessels. As mentioned earlier in this report, the differences in performance could have been caused by an experience factor. Each pilot made four runs, in addition to the two familiarization runs, and there was a question of whether or not the performance demonstrated on the later runs was different than on the earlier runs. (The ship-order vs run-order for each pilot differed, as indicated in Table 2-1.) The experimental data was therefore regrouped by "run-order" and the same series of analyses were performed as for "ship-order." Significant differences for the "run-order" comparisons were small in number. This indicates that the experimental design *did* truly eliminate most of the experience and fatigue factor effects on the findings associated with the primary variables.

3.2.3.1 Ship Speed, VOS

The run-order findings for the VOS performance measure are illustrated in Figure 3-17. In leg 2 the average speed on the fourth run was significantly larger than any of the previous runs and the ship speed in the first data run was slower than any of the following runs. In the 90° turn VOS for the first run was significantly smaller than for runs 3 and 4, and in leg 6 the speed for the first run was found to be smaller than for the penultimate and last runs. It would appear that the differences which were found reflect the fact that the pilots tended to increase their ship speed as they performed additional runs to maintain control, as shown in the total channel findings (Figure 3-18). Since most of the differences were found in leg 2 though, just after the approach phase, the findings could also reflect a desire on the test subjects part to shorten the overall passage during the approach phase, where no speed limit was imposed. Although told of this allowable unlimited speed in the approach leg at the outset of their runs, it appears that they assimilated this knowledge as the runs progressed, and a spillover of increased speed as a function of run order in leg 2 resulted.

The ability to decrease VOS at end of leg 6 was investigated by means of a measure called End of Run VOS. This measure was analyzed for ship effects and run-order effects but neither analyses yielded significant differences.

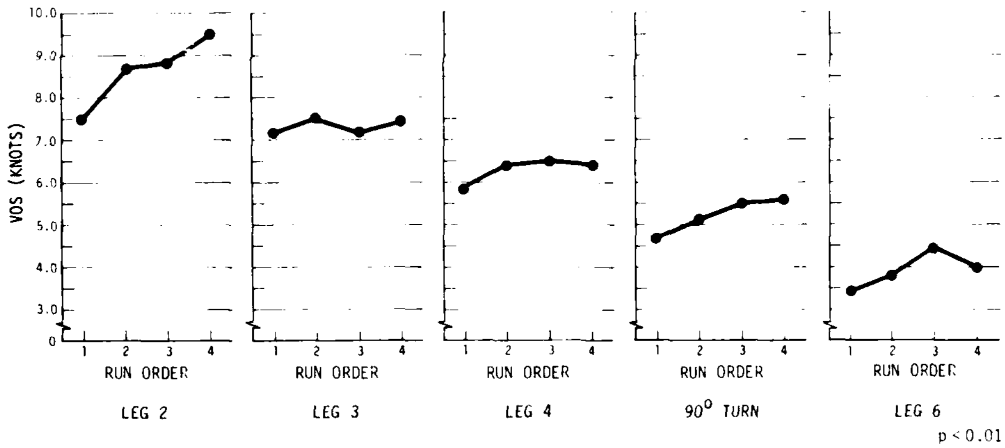


Figure 3-17. Run-Order Effect Comparison - VOS By Leg

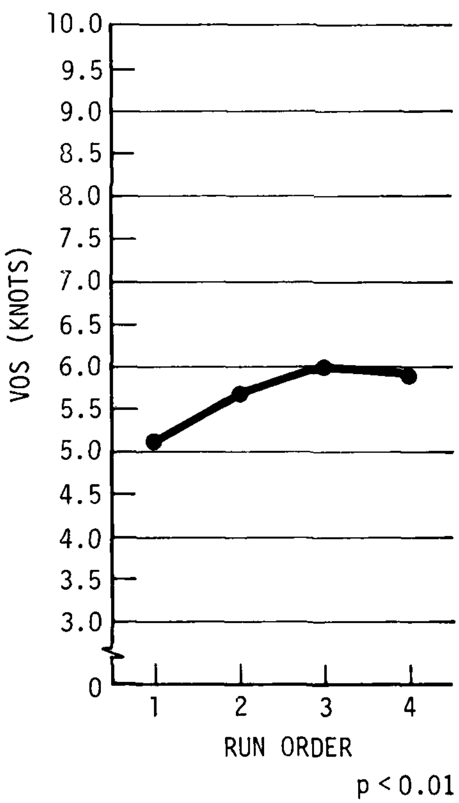


Figure 3-18. Run-Order Effect Comparison - VOS - Total Channel

Since the speed limit differed in the last leg, compared with the previous legs, an additional ship speed related function was investigated, namely the elapsed time necessary to traverse legs 2, 3, 4 and the 90° turn. These legs all had the same speed limit of 7 knots and this was actually a partial channel transit time, for all but the last leg. There were no significant differences found for this performance measure when the data were grouped by ship, but when grouped by run-order there was a significant finding at the $p < 0.01$ level. The results are indicated in Figure 3-19. They show that the "partial" time for run 1 was approximately five minutes longer than for the other three runs (39.5 minutes compared with 36.4, 35.9 and 35.2 minutes), and that the run-order effect for VOS noted above was most probably not caused by differences in speed within the last leg.

3.2.3.2 Rudder Commands, R_T

The findings for the run-order comparison of the performance measure R_T (i.e., rudder command rate) are presented in Figure 3-20. The differences which were found to be significant were at the minimum reporting level of $p < 0.05$ and showed that the number of rudder commands per minute issued by the pilots was smaller for leg 2 (run 1 compared to run 2) and the 90° turn (run 1 compared to run 3).

3.2.3.3 Closest Point of Approach to Entrance Buoy #1

The shear current at the channel entrance, along with the beam wind, tended to push the ships to port, towards Buoy #1. The entrance to the channel was 1000 feet wide so that the centerline desired track within leg 2 was 500 feet from Buoy #1. The Closest Point of Approach (CPA) to Buoy #1 was used as a measure to indicate control at the channel entrance and the ship comparison for the measure was not found to be significant. The run-order comparison, however, did show significant findings as indicated in Figure 3-21. The average CPA of the center of gravity of all ships during the first run was 320 feet, for the second run 396 feet, for the third 466 feet and for the fourth 447 feet. It is apparent that these finding underscore a learning function since the pilots managed to accommodate the entrance problems and, on average, brought their vessels within 1/2 ship beam width (62.5 feet) for the third and fourth runs, regardless of the ship that was being conned. Analyses of the sixteen individual runs that contributed the data for the aforementioned averages indicate that in four instances Buoy #1 was actually struck by the ship (Table 3-1). In each case this ocurred during either run 1 or run 2 and when the pilot was on Ship B, C, or E. These data underscore that this was a learning effect, not a ship effect.

3.2.4 Difficulty Measure

The performance that was exhibited by the pilots as they maneuvered the four different vessels through the channel was variable and depended on both the ships and the pilots themselves. The performance measures recorded during the runs have been used in the previous paragraphs to statistically compare these transit performances on an "averaging" basis, i.e., average per ship, average per leg or average for the whole channel passage. An alternative method exists for describing the relative performance of the pilots during the channel transit and involves a graphic/analytical procedure. The passage for each

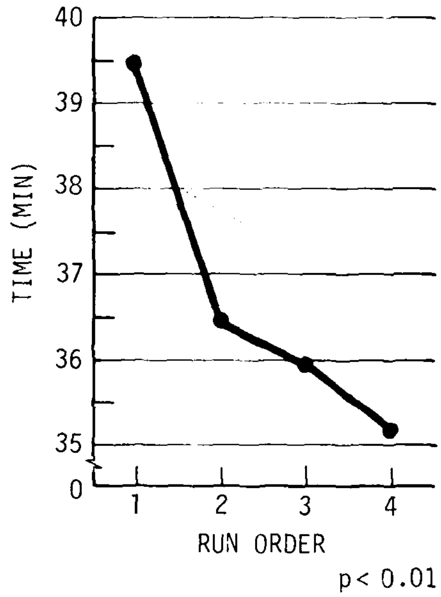


Figure 3-19. Run-Order Effect Comparison - Transit Time - Leg 2 Through 90° Turn

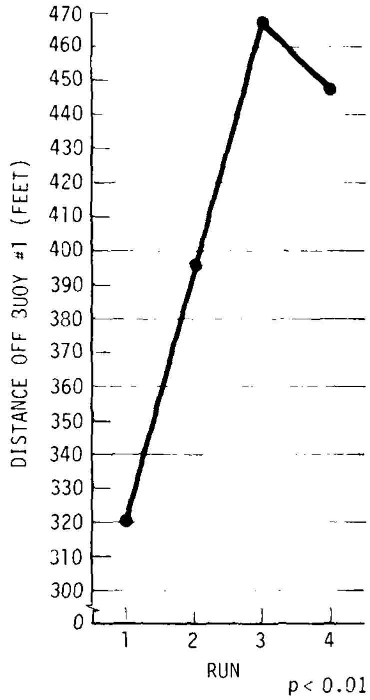


Figure 3-21. Run-Order Comparison - CPA to Buoy #1

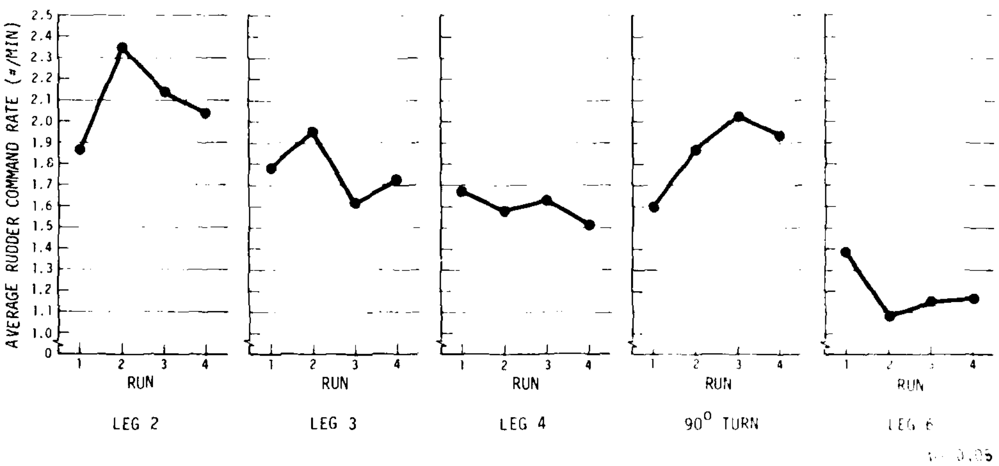


Figure 3-20. Run-Order Effect Comparison - Rudder Command Rate By Leg

TABLE 3-1. BUOY #1 INCIDENTS

	Run 1	Run 2	Run 3	Run 4
Ship A	0	0	0	0
Ship B	1	0	0	0
Ship C	1	1	0	0
Ship E	1	0	0	0

pilot on each ship had been recorded and a track plot of each total channel run was produced. These sixty-four run/plots were grouped by pilot into sixteen composite figures and are shown as Figures 3-22 through 3-37. There is one figure for each pilot consisting of the four runs associated with that pilot. Within each figure, they are displayed in run order, i.e., the plot on the extreme left is the pilot's run on his first ship, the second from the left, his second run, etc. Since the run order for each pilot was different, each of the composite plots is identified with the ship type (A, B, C or E) under the appropriate portion of the figure.

These plots give an overview of each run and together establish the performance demonstrated during the complete experiment. It is apparent, upon examination, that most portions of the channel runs were "uneventful" in that the ship tracks are most often quite close to the desired centered track line. The variability in performance between pilots and pilot/ship combinations becomes most apparent in three areas: the channel entrance at the start of leg 2, the pullout from the starboard turn at the start of leg 4 and the overshoot at the end of the 90 degree turn — either the end of leg 5 or the start of leg 6. The fact that performances are most variable in these areas and differ from the desired track, implies that it is there that the greatest amount of difficulty is created for the pilots during each of their transits. Also, since the performances differed primarily in these areas, the effects of the area on pilot/ship combinations differed. Consequently the difficulty experienced by the pilot in overcoming problems with the inherent maneuvering characteristics of each vessel differed. By quantifying the performance difficulty in these three areas for each run, an additional performance measure evolved allowing additional comparisons to be made between performances exhibited by each of the pilots on each of the ships. Normally averages over a leg or the whole run tend to desensitize a performance measure, because of the inclusion of the large "uneventful" portions of the transit. This measure of difficulty pinpointed the problem areas and therefore tended to sensitize the differences in performance which were caused by differences in inherent maneuvering characteristics of the four ships.

The quantifying technique that was used by the experimenter was to rank the performance on each ship at each of the critical areas for each pilot, with a rank of 1 assigned as the lowest or poorest and a rank of 4 representing the highest or best. For each pilot the three area rankings for each ship tran-

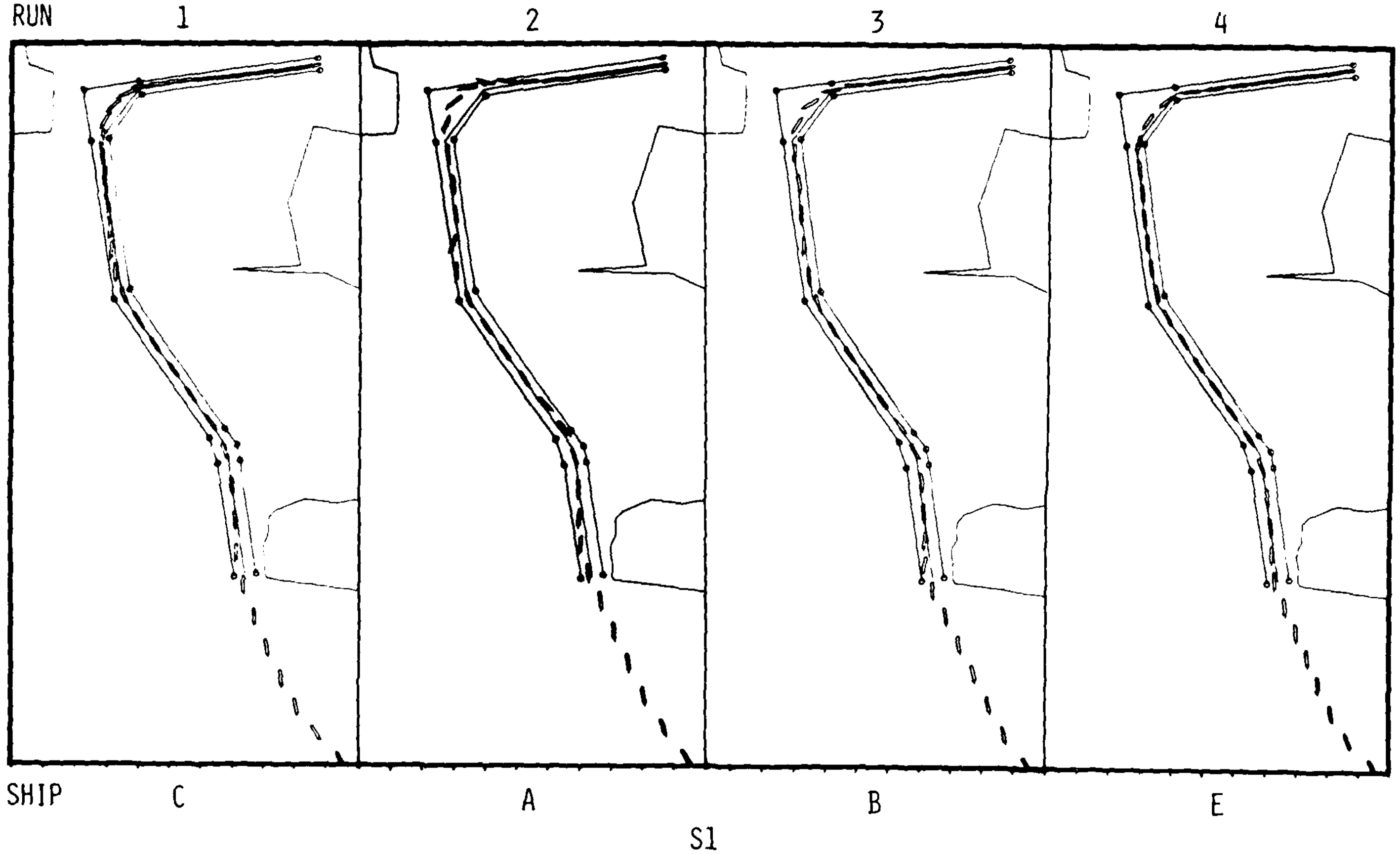


Figure 3-22. Individual Subject Track Plots - S1

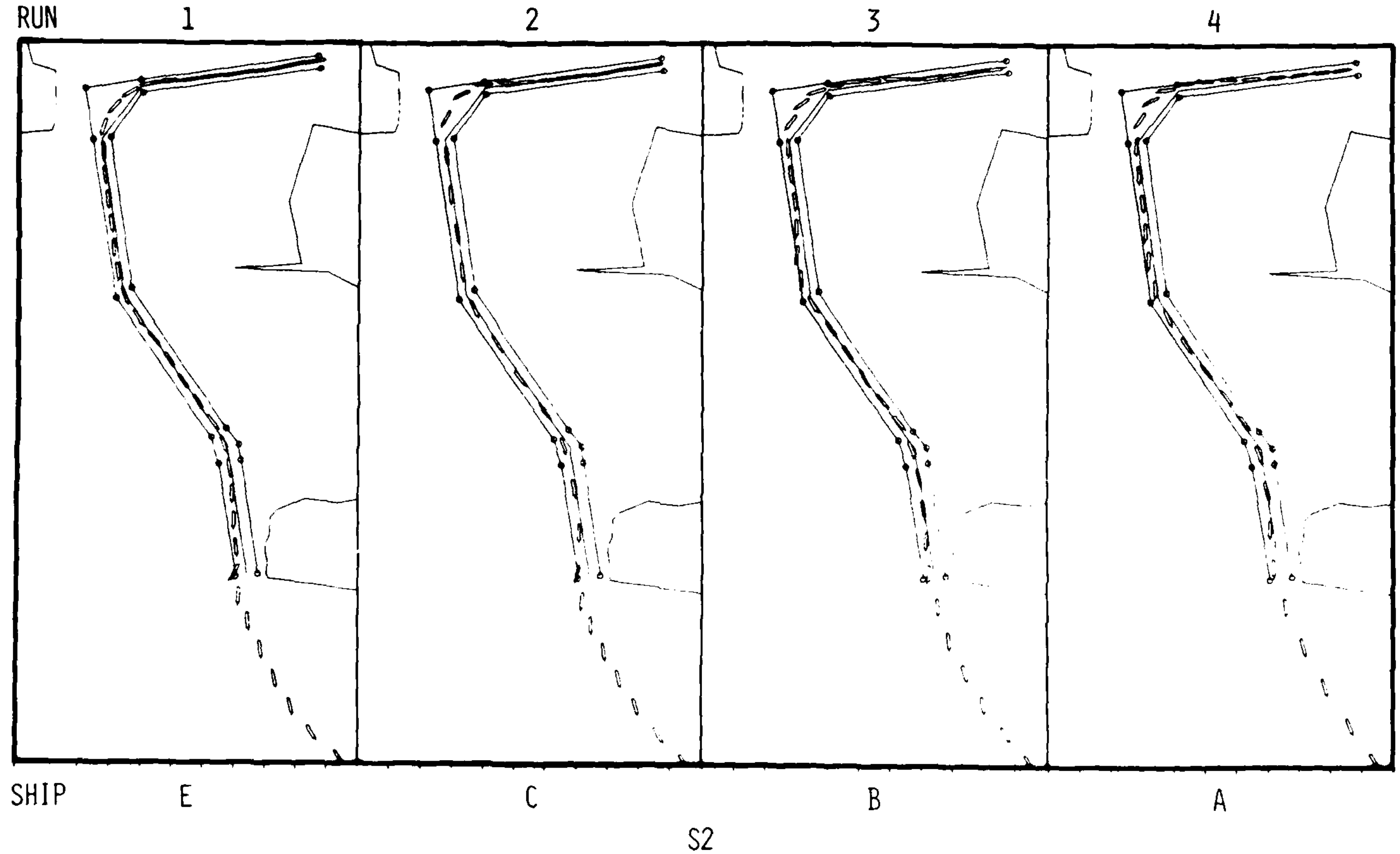


Figure 3-23. Individual Subject Track Plots - S2

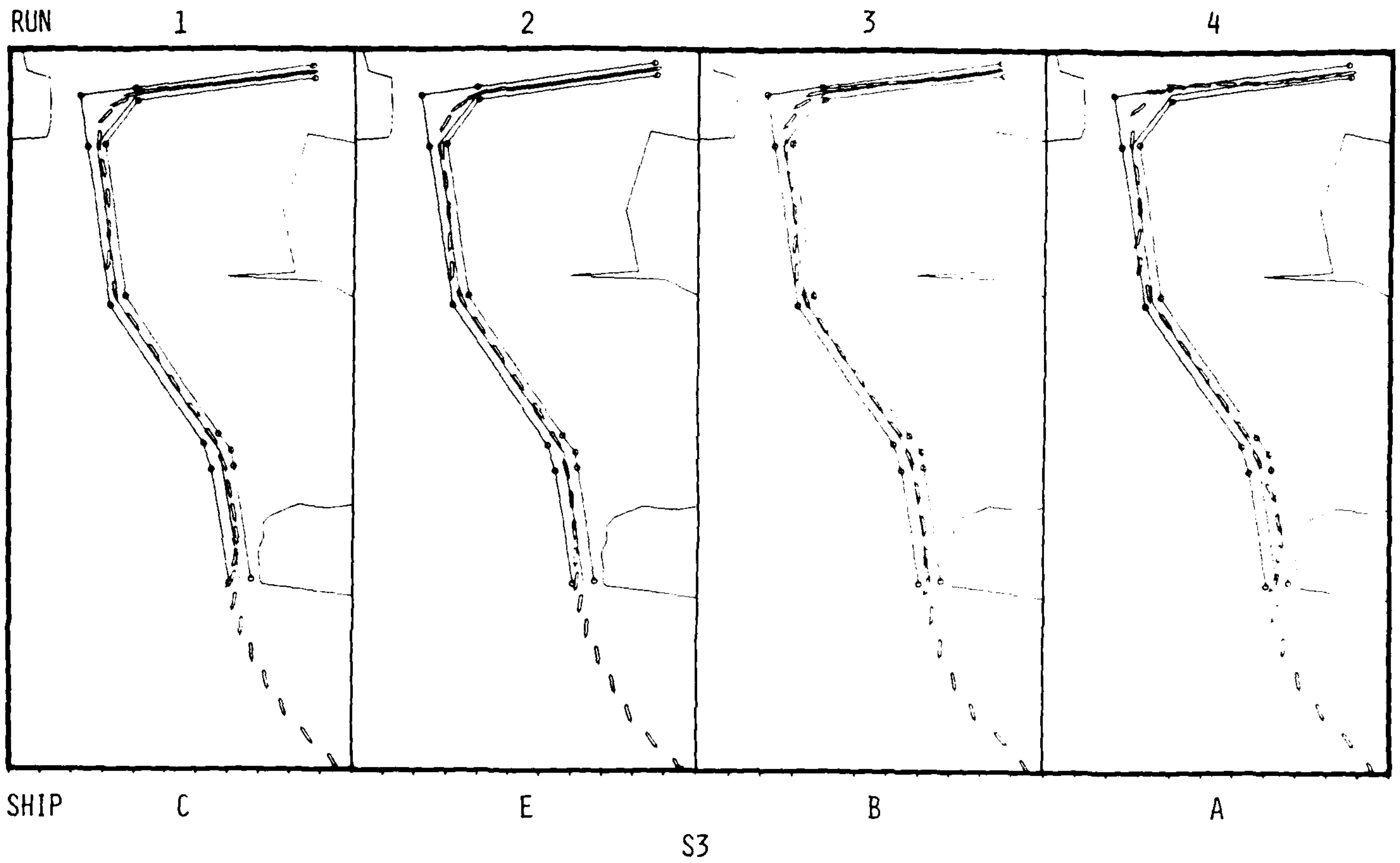


Figure 3-24. Individual Subject Track Plots - S3

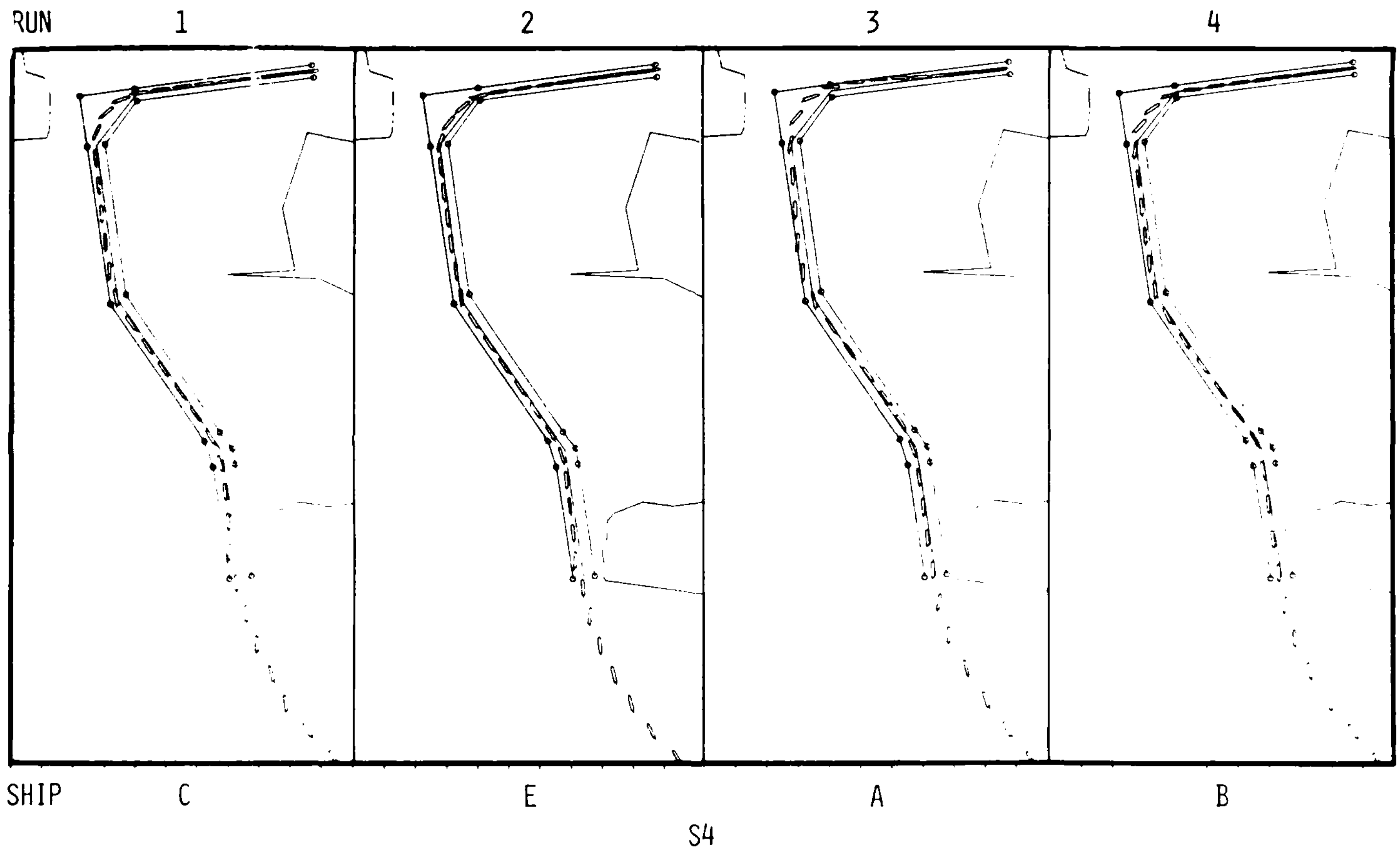


Figure 3-25. Individual Subject Track Plots - S4

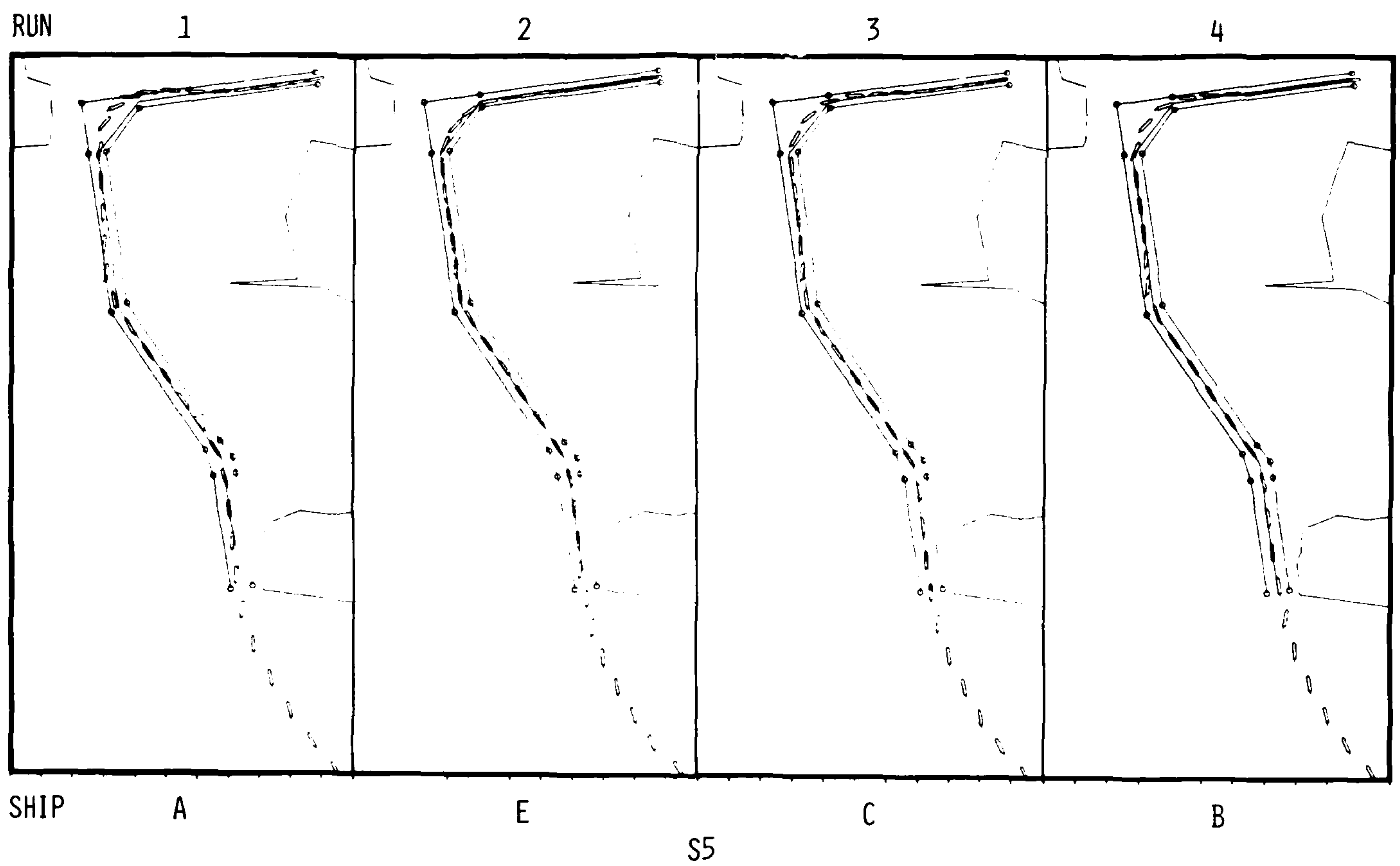


Figure 3-26. Individual Subject Track Plots - S5

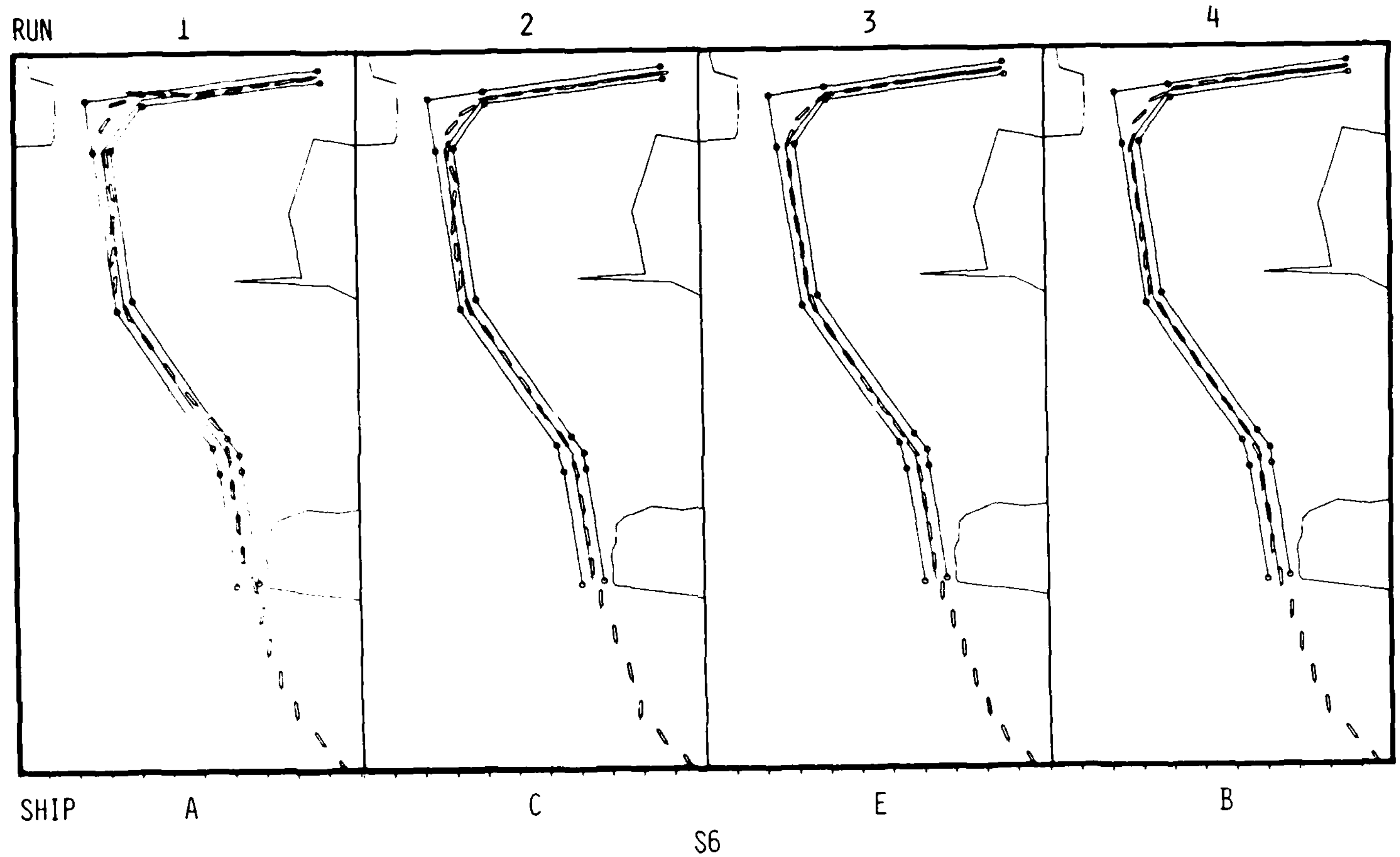


Figure 3-27. Individual Subject Track Plots - S6

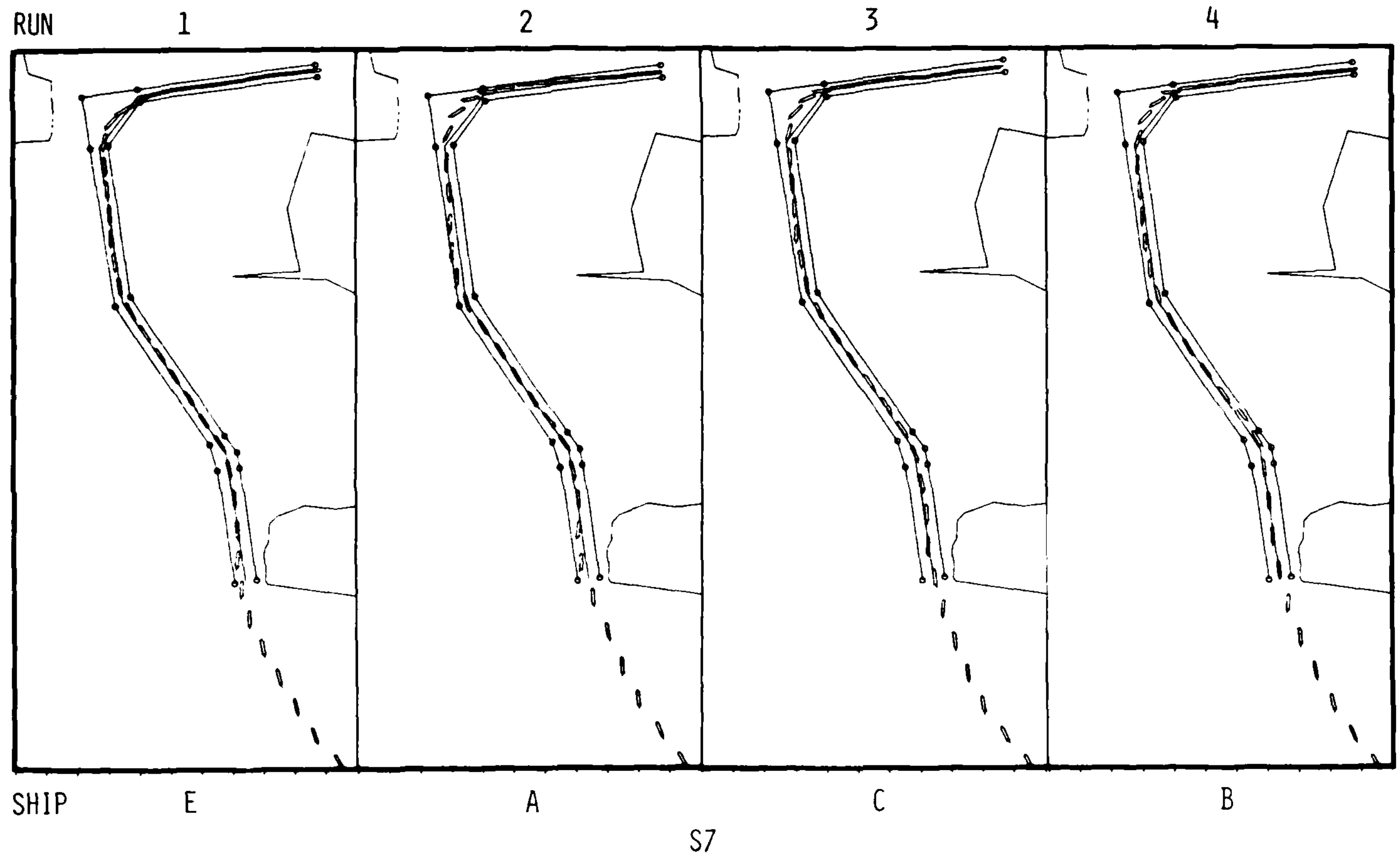


Figure 3-28. Individual Subject Track Plots - S7

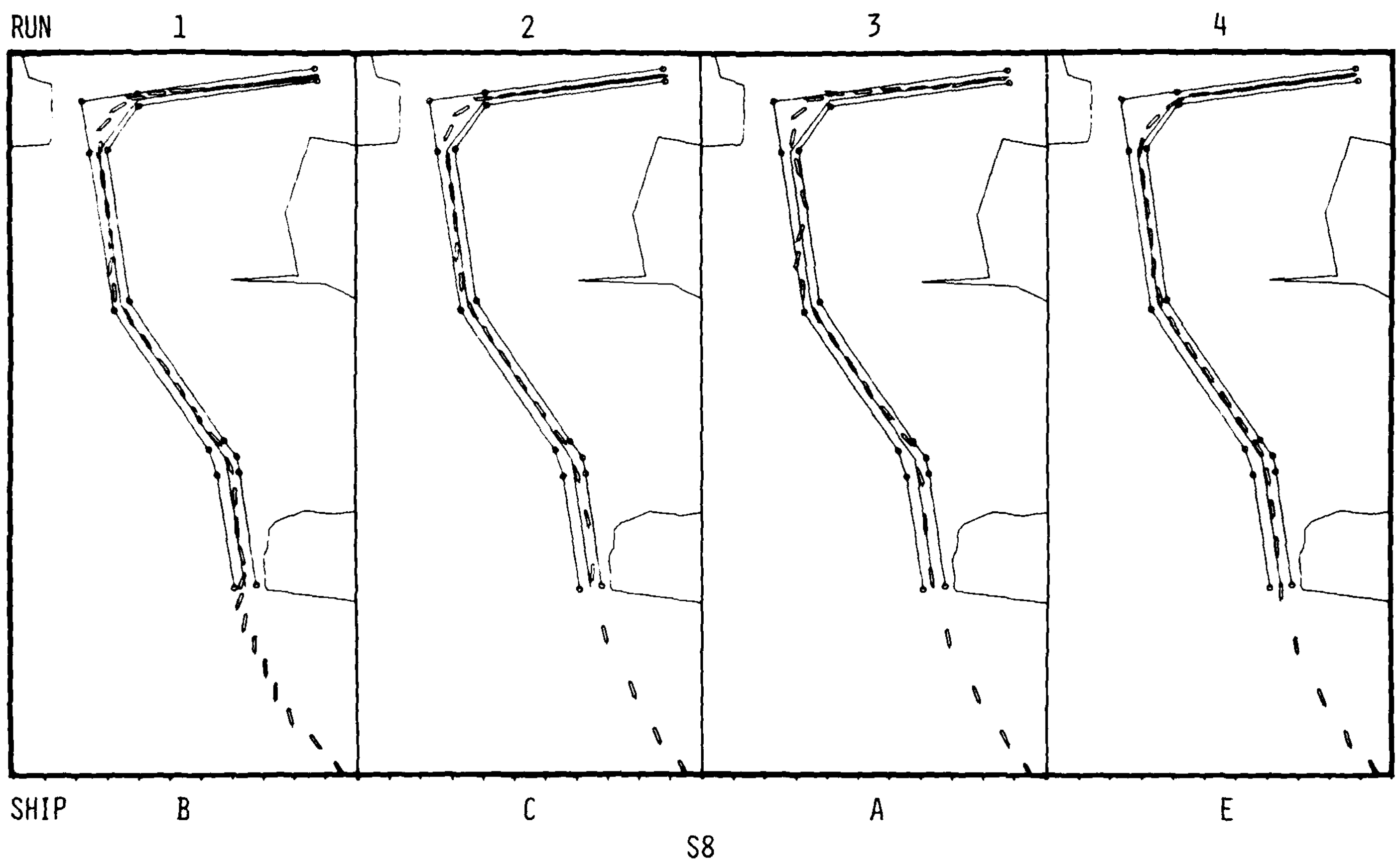


Figure 3-29. Individual Subject Track Plots - S8

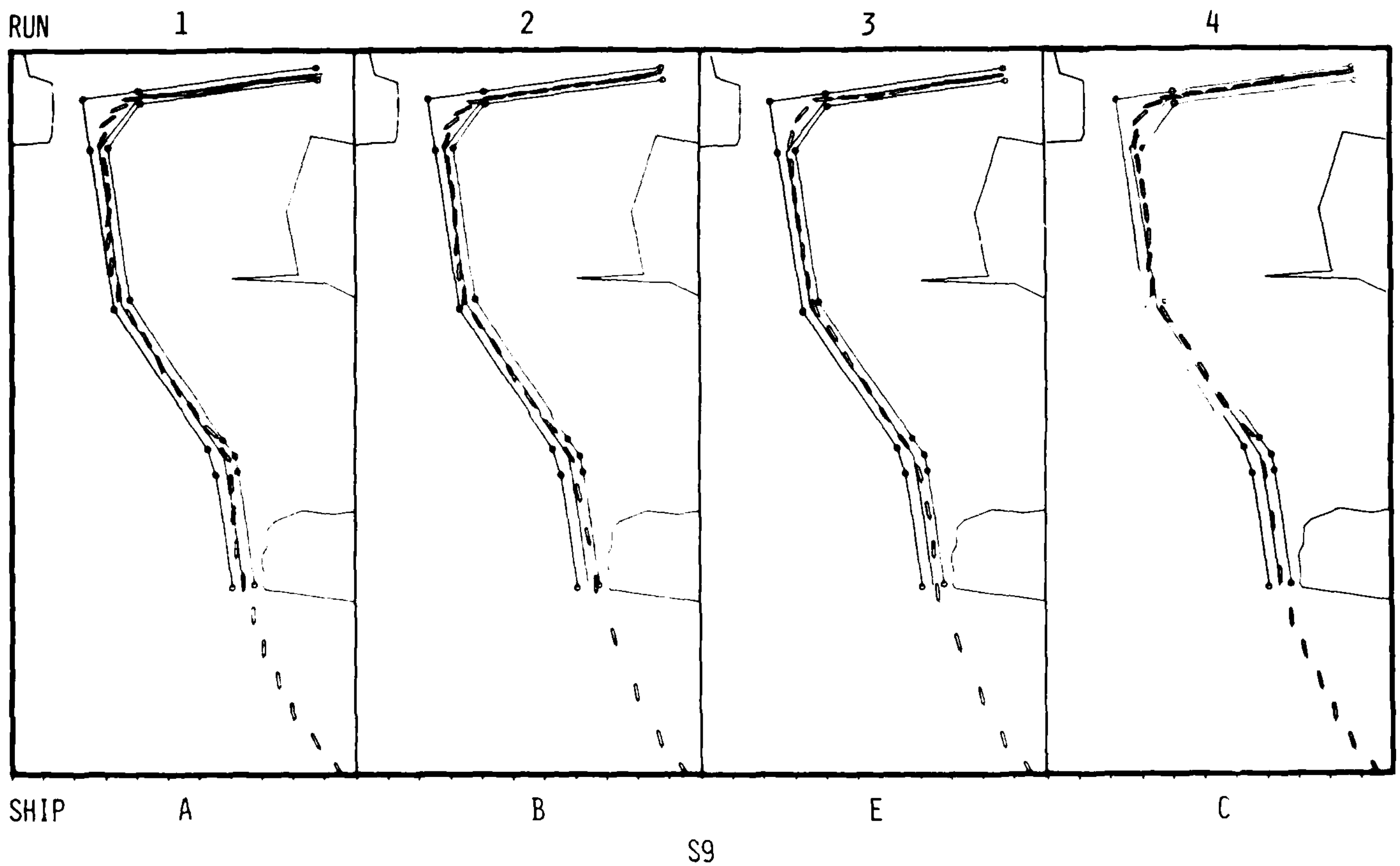


Figure 3-30. Individual Subject Track Plots - S9

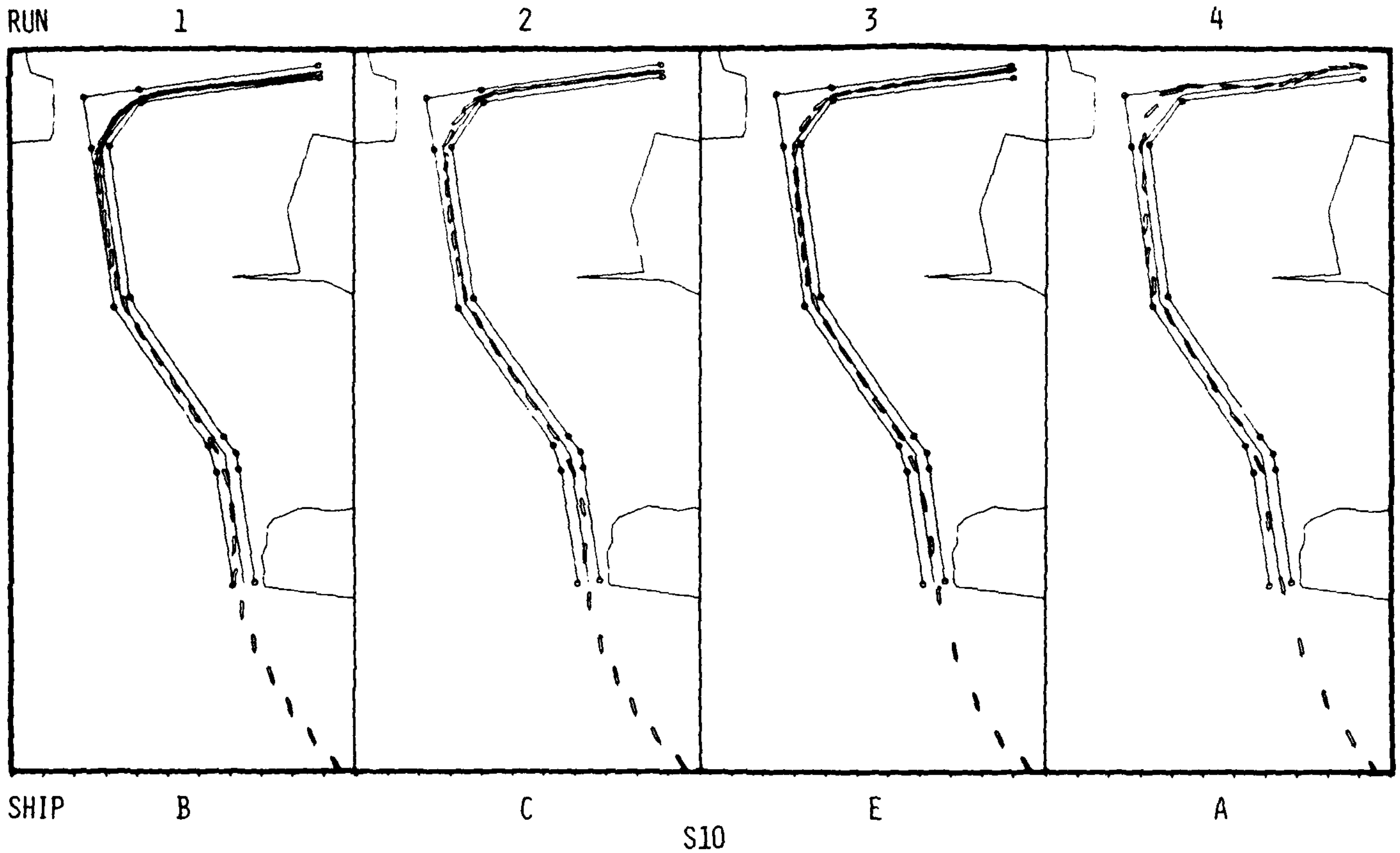


Figure 3-31. Individual Subject Track Plots - S10

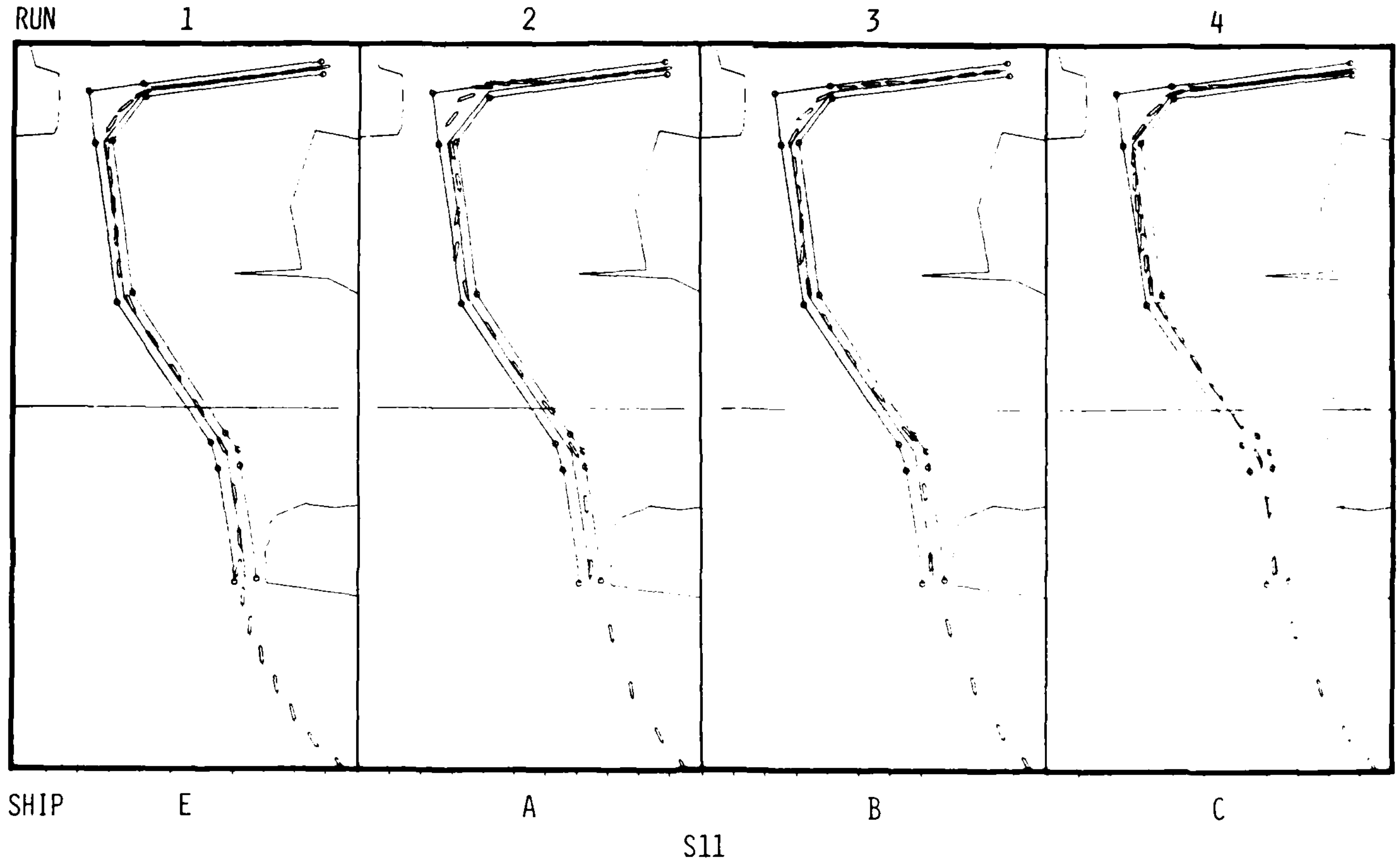


Figure 3-32. Individual Subject Track Plots - S11

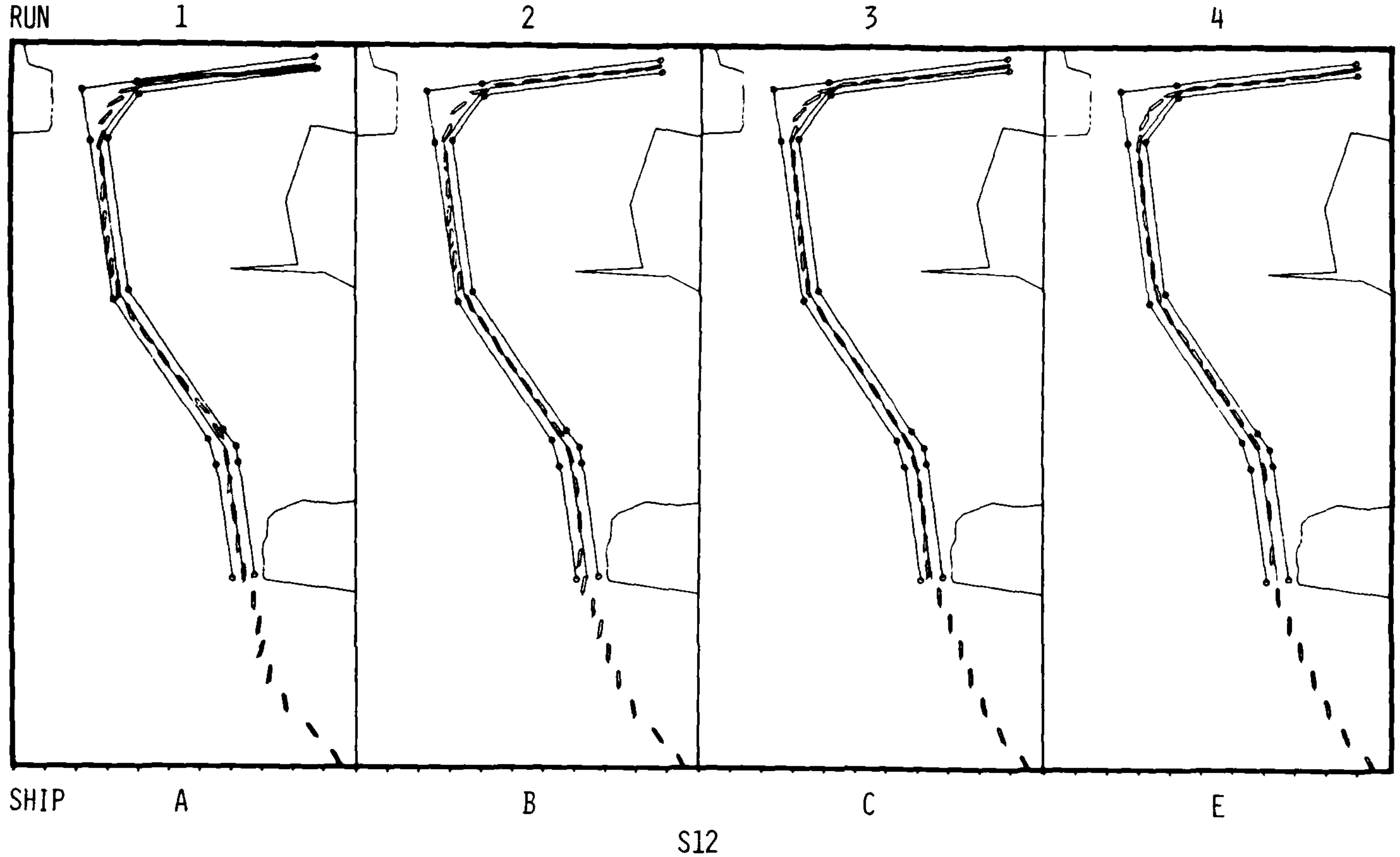


Figure 3-33. Individual Subject Track Plots - S12

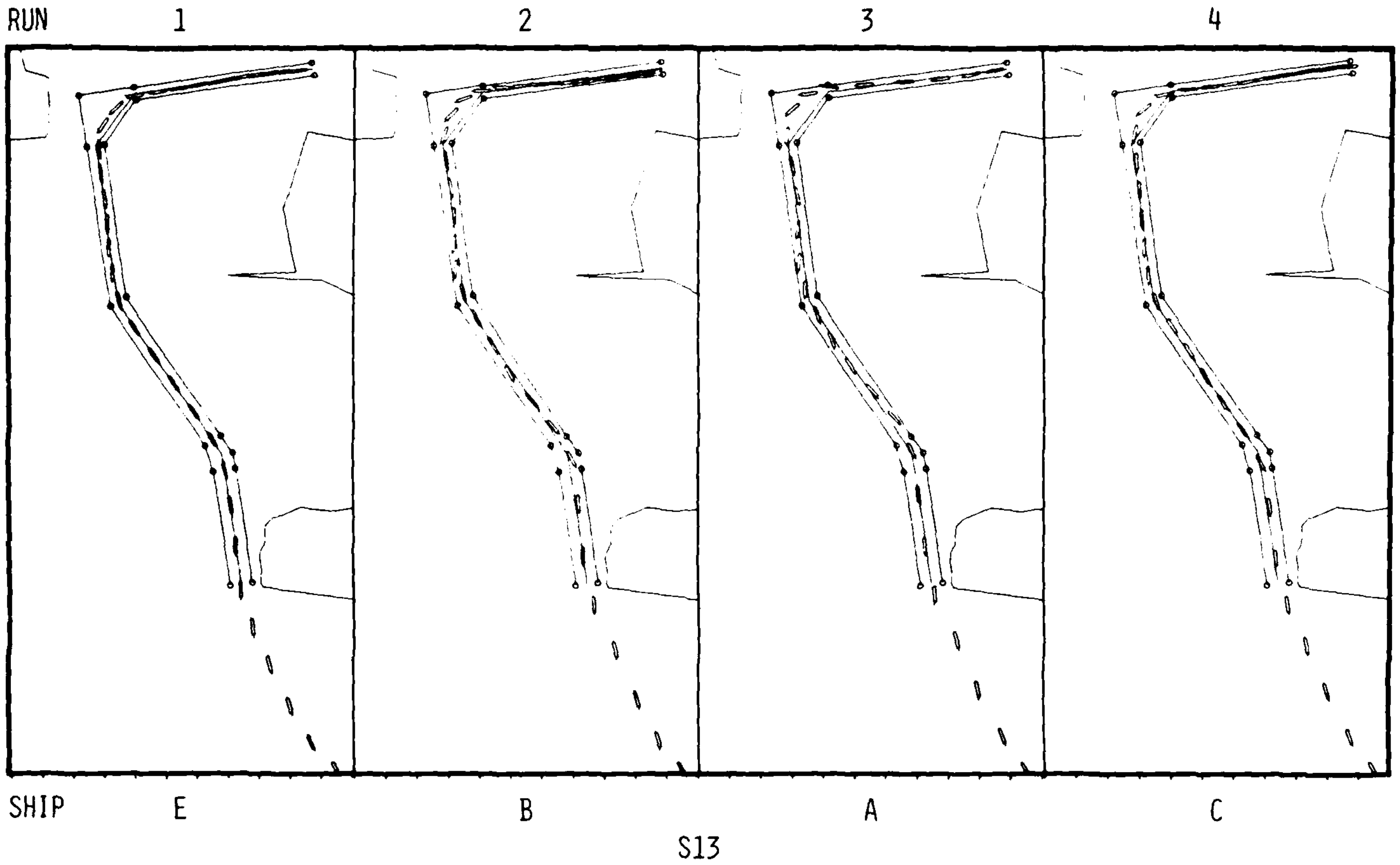


Figure 3-34. Individual Subject Track Plots - S13

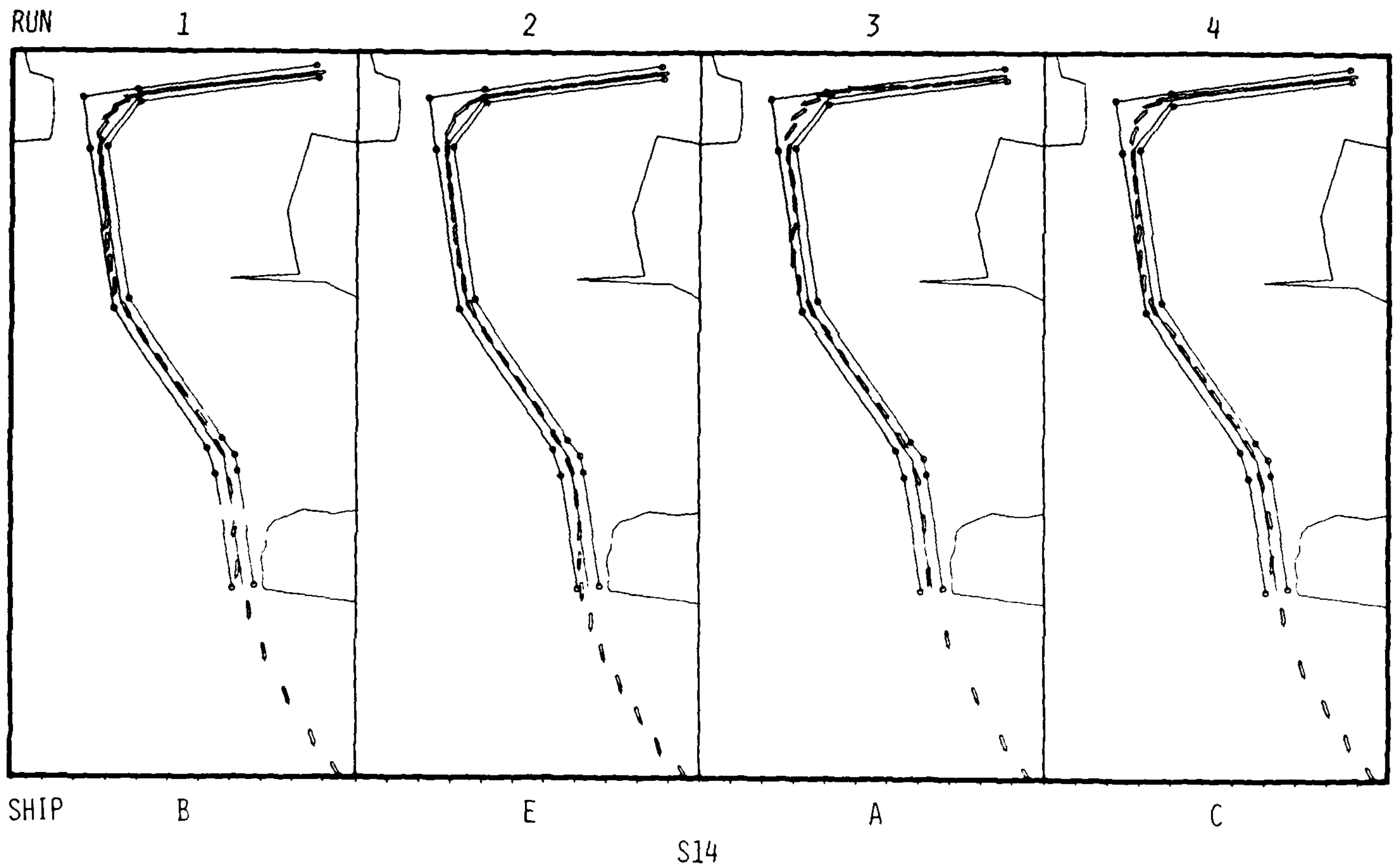


Figure 3-35. Individual Subject Track Plots - S14

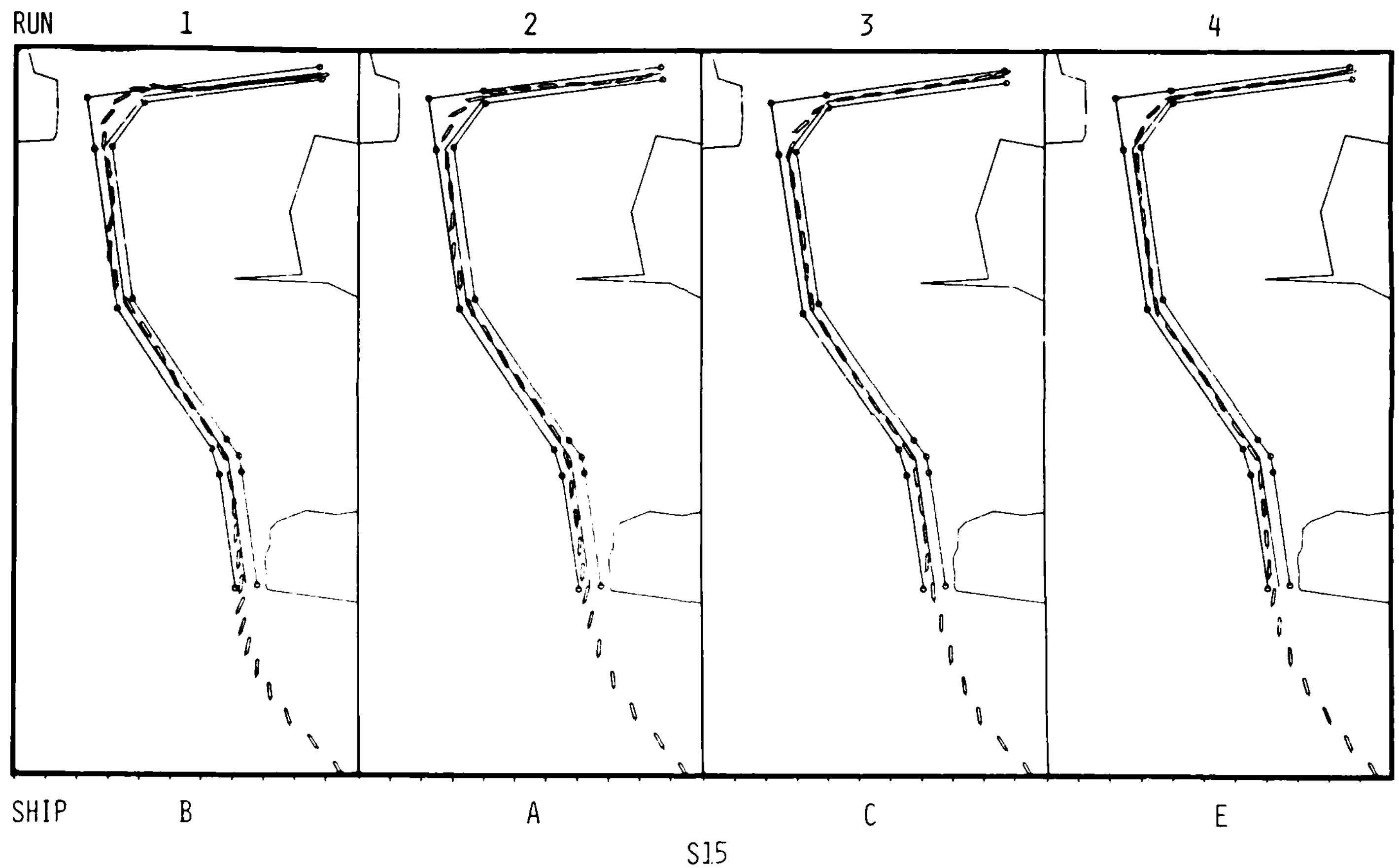


Figure 3-36. Individual Subject Track Plots - S15

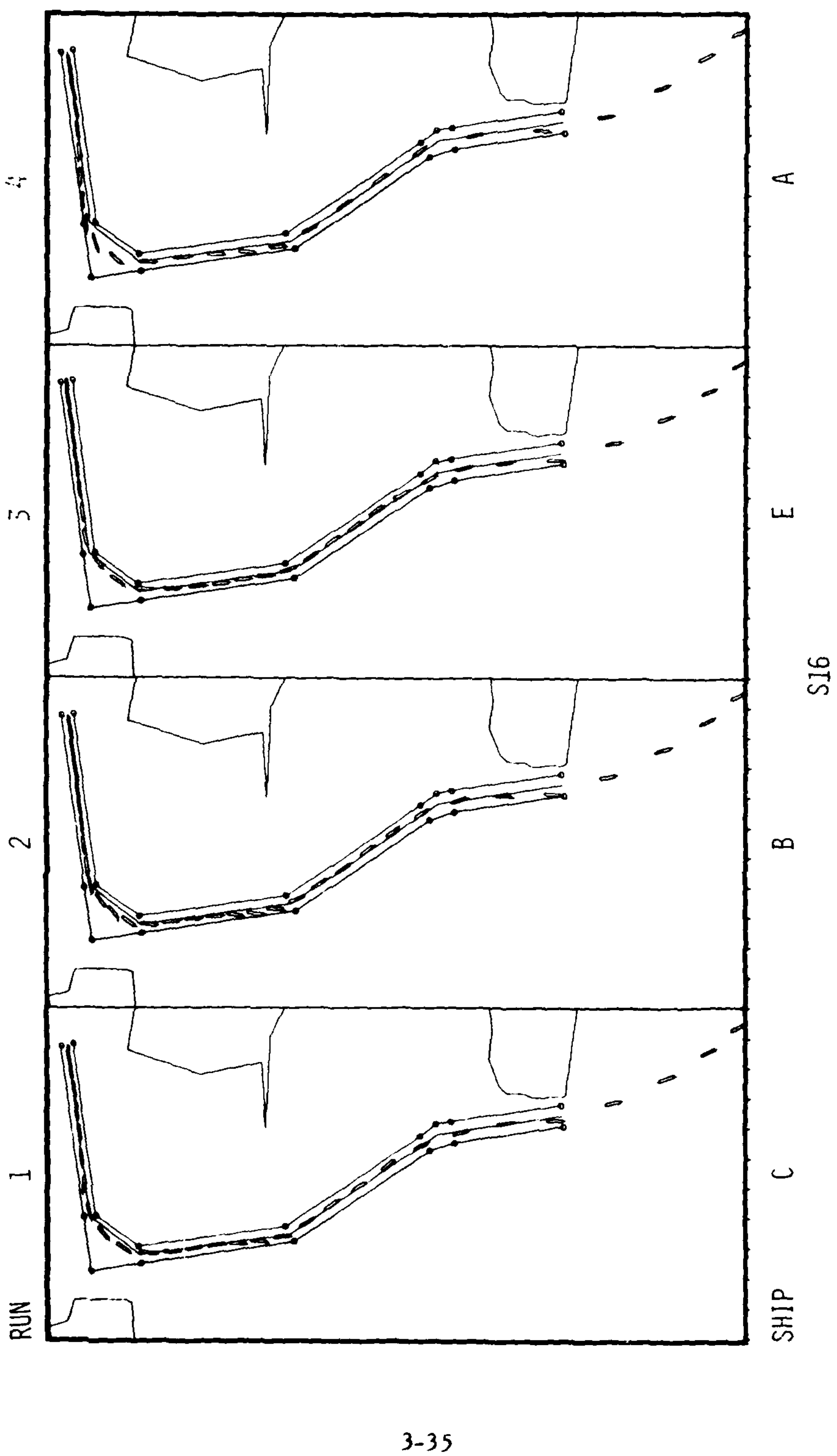


Figure 3-37. Individual Subject Track Plots - S16

sit (run) were then averaged and the resultant scoring then used to attain an overall ship (run) ranking for each pilot. An example will best clarify this procedure. Table 3-2 indicates the technique as it was used for Subject 14, resulting in an overall Difficulty Ranking of 1 for Ship A, 2.5 for Ship B, 2.5 for Ship C and 4 for Ship E. These Overall Rankings were based on the Average Area Ranking of 2, 2.5, 2.5 and 3 respectively. The 2.5 ranking for both Ships B and C indicates that the second and third overall Difficulty Rankings were equal (because their Average Area Rankings were equal), therefore the average of the two (2 and 3) was used. It should be noted that the analyses (i.e., rankings at the three problem areas) were conducted using the original plots which are much larger than are shown in Figures 3-22 through 3-37. In addition further determinations of distance off-track were made, when necessary, based on quantitative data which had been obtained from the recordings of each run.

Table 3-2 also shows a similar ranking for Inherent Maneuverability of each ship with the unstable vessel (A) given the poorest rank (1), and the most stable ship (E) given the highest rank (4). This ordering has also been applied to runs in that the first run is given the poorest rank, i.e., 1, and the fourth given a 4. By means of these latter assignments the difficulty ranking of ships for each pilot can be correlated with the Inherent Maneuverability ranking by ship as well as the Run Order ranking. The correlation coefficient is a measurement of how well the difficulty experienced by the pilots during a channel passage corresponds to the ship that was used or the order in which the runs were accomplished. A high positive ship-effect coefficient would indicate that the pilot had difficulty with the channel transit which correlated with ship stability factors and a low correlation would mean that the pilot found the ships equally difficult (or easy) to handle. A high positive run order effect implies that learning was in

TABLE 3-2 DIFFICULTY RANKING FOR SUBJECT #14

Order Ranking	Inherent Maneuverability Ranking	Area Ranking				Overall Difficulty Ranking
Run	Ship	Entrance	Stb. Turn	90° Turn	Average	Difficulty
1	2 (B)	2	3	2.5	2.5	2.5
2	4 (E)	1	4	4	3	4
3	1 (A)	4	1	1	2	1
4	3 (C)	3	2	2.5	2.5	2.5

evidence since it would show better performance (less difficulty) on subsequent runs. A small positive or small negative coefficient would imply no relationship between run order and difficulty while a large negative coefficient could possibly indicate fatigue; that is, poorer performance with the later runs. In the example given there was a correlation of +0.95 between Difficulty and Inherent Maneuverability for subject 14 and -0.25 for Difficulty and Run-Order.

A summary of the result of the Performance Difficulty Correlation analyses are shown in Figure 3-38 (A and B). Both figures contain the cumulative curve of number of test subjects vs. correlation coefficient. The Inherent Maneuverability Characteristics curve Figure 3-38A indicates that half of the total number of test subjects (8) displayed performance difficulty which correlated with Ships (i.e., stability) at a level greater than or equal to a coefficient of +0.95. The average for the sixteen subjects was +0.813 and thirteen of the sixteen displayed performance correlating at +0.8 or higher. The results of the analyses using this performance measure clearly indicate that the pilots had difficulties with the transiting of the channel which were highly correlated with the stability of the vessel used; more difficulty at the three problem areas on ships which were less stable and, conversely, less difficulty with the more stable vessel(s). This finding mirrors the results that were found with the averaging techniques discussed earlier with the ANOVA comparisons.

In contrast to Figure 3-38A, Figure 3-38B indicates that correlation of performance with Run-Order was weak to non-existent; a correlation coefficient of only +0.4 or more was found for half the test subjects and the average correlation between Performance Difficulty and Run-Order was +0.206. This indicates that the number of familiarization runs used in the experiment were sufficient to familiarize the test subjects with the channel (no learning effect in the experimental data) and the number of runs were not excessive (a fatigue factor did not emerge).

Yet another question exists regarding this area of performance difficulty and that is whether or not the pilots accurately perceived their difficulties. Are they alerted to problems that actually exist or do other factors confound this perception? During the pilots' debriefing they were asked to rank their four runs in accordance with difficulty in ship handling; essentially, which ships were easiest, hardest, etc. Table 3-3 contains the results of these debriefings and is discussed further in Section 3.5.

These subjective perceptions of the passages were compared with the actual recorded performances to obtain a measure of the pilots' perception of their difficulties. The comparisons were again made by means of ranking with the Perception Ranking based on the debriefings. The Perception of Difficulty comparisons, (i.e., correlations) were made with actual Difficulty Ratings, Inherent Maneuvering Characteristics ratings as well as Run-Order ratings. The results are shown in Figure 3-39 (A, B and C), which indicate cumulative test subject population vs. correlation coefficients for each of the comparisons. Figure 3-39A contains the findings for the Perception vs. Actual Difficulty and 3-39B for the Perception vs. Inherent Maneuverability comparison. These two findings show comparable results. Both indicate that a correlation coefficient equal or greater than +0.8 was obtained by 8 of the 16 subjects

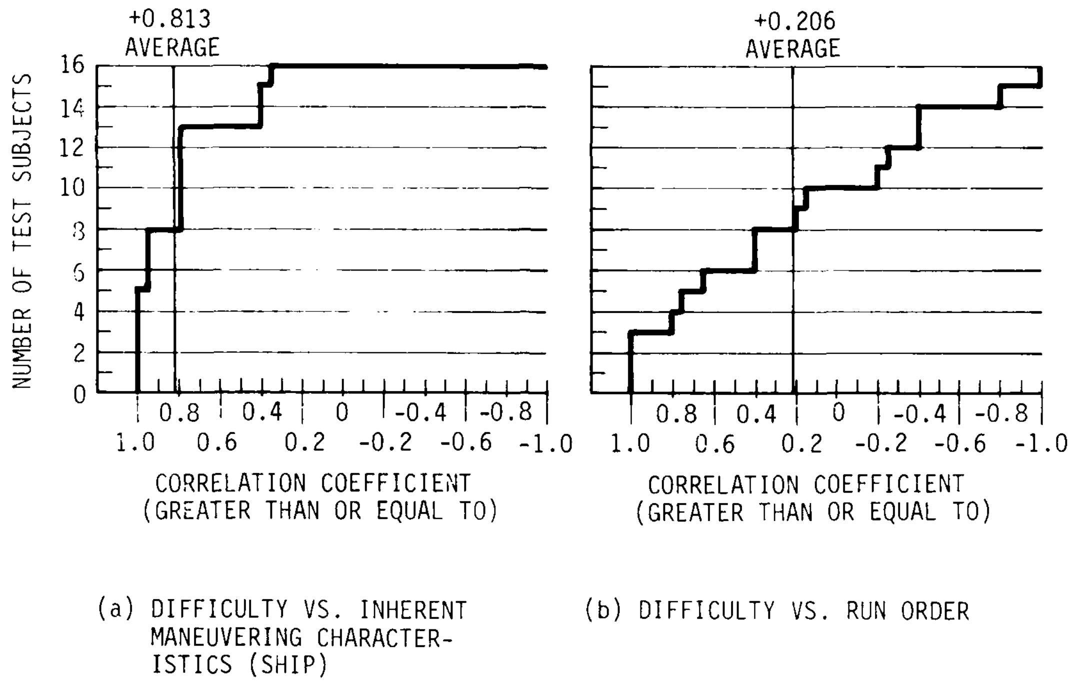
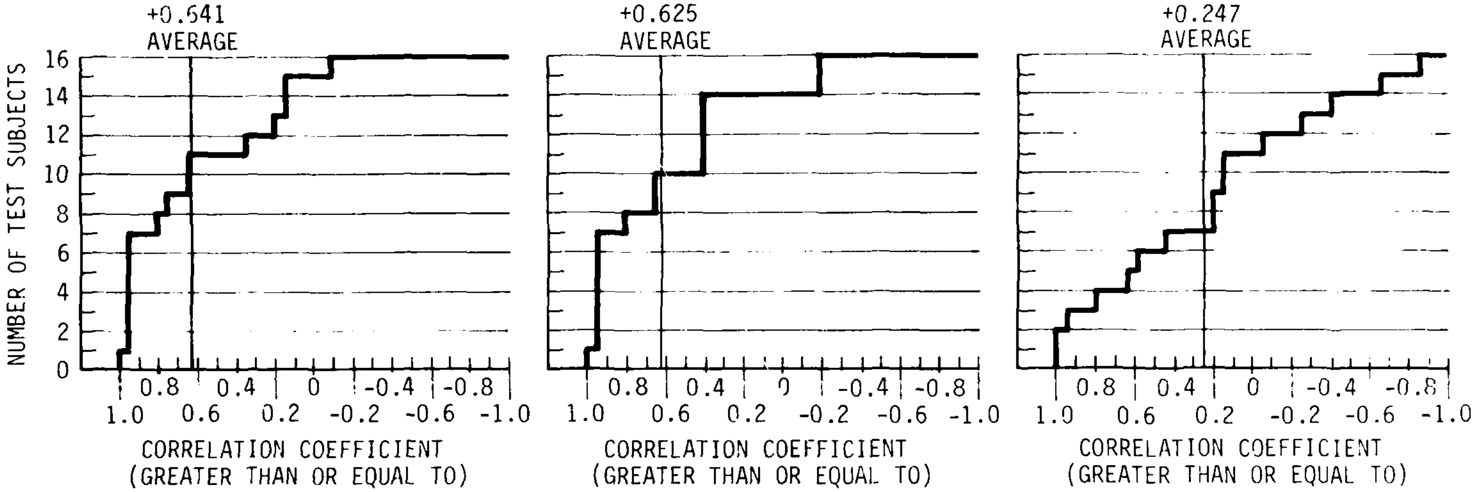


Figure 3-38. Difficulty Analyses - Cumulative Number of Test Subjects vs. Correlation Coefficients

TABLE 3-3 PILOT PERCEPTION OF DIFFICULTY

Subject	A	B	C	E
1	1	2.5	2.5	4
2	4	1	2	3
3	1	2	3.5	3.5
4	1	2	3.5	3.5
5	1	3	3	3
6	1	4	2	3
7	1	3	4	2
8	1	2	3	4
9	1	4	2	3
10	1	2.5	2.5	4
11	2	3	4	1
12	1	2	3.5	3.5
13	1	2	3.5	3.5
14	1	4	2	3
15	1	3.5	2	3.5
16	1	2.5	4	2.5



(a) DIFFICULTY PERCEPTION VS. PERFORMANCE DIFFICULTY

(b) DIFFICULTY PERCEPTION VS. INHERENT MANEUVERING CHARACTERISTICS (SHIP)

(c) DIFFICULTY PERCEPTION VS. RUN ORDER

Figure 3-39. Perceived Difficulty Analyses - Cumulative Number of Test Subjects vs. Correlation Coefficients

and that the average value was approximately two-thirds (+0.641 and +0.625). The Run-Order comparison of Figure 3-39C indicates that half the test subjects obtained a Perceived Difficulty which correlated at a level greater than or equal to +0.200, with an average of +0.247, i.e., no correlation was evidenced. The findings from this second series of correlation analyses imply that the pilots' perceptions were fairly accurate. They were capable of recognizing when they were having difficulties, and which of the ships were more difficult to handle. It can also be suggested that familiarization with the channel (run order) was not a factor in their determination of the difficulties they were experiencing due to the ship differences.

3.3 SUMMARY GROUND TRACKS

The data of the sample grouping of pilots used in the experiment have also been assembled and presented within this section as graphical representations of the average ground track for each of the vessels used during the channel transits.

The basic chart for the presentation of this information is shown in Figure 3-40 and indicates the channel legs with all turns eliminated. As with the previous analyses the approach phase (leg 1) is considered to be a ship familiarization phase and therefore not used for comparitive performance evaluation purposes. The left hand "start of chart" is therefore just prior to leg 2 and is labeled 1.5 nm from starting point. The first leg of the channel (leg 2) is 1000 feet wide followed by two narrower segments of 800 feet each, (leg 3 and 4). The channel outline for the 25° turns is only symbolically represented, as is that of the 90° turn (leg 5). The 600 foot leg (#6) is the final leg that is shown on the chart. The channel buoys and the desired centerline track are also appropriately indicated. The track has been straightened into a single continuous line for ease of visualization and comparisons of distances from the desired track line. Data locating the athwart channel ship position are presented for each summary track at one-eighth nautical mile increments and are based on the results obtained from all subjects on each of the ships. For example, the sixteen pilots each transited the "ABC" harbor on Ship A. For each 1/8 nm position along the track the sixteen values of off-track deviation for Ship A were averaged, a standard deviation was computed and the largest and smallest values of off-track deviation were noted. At each appropriate position along the track for Ship A the average value of distance off track was plotted relative to the channel centerline and a line centered at the average, with a total length equal to two standard deviations (i.e., two sigma) was also drawn. Ship passage is from left to right on the chart with deviation to the right of the center channel line plotted below the center channel position and a deviation to the left plotted above. The maximum and minimum points were indicated by stars at each position. The repetitive plotting of these pertinent data from each 1/8 mile position in the five legs allows for an overview of performance in Ship A as well as on each of the other three vessels. The data used were based on the track of the center of gravity of each ship, and therefore do not account for the length, breath or alignment of the ships themselves.

3.3.1 Summary Track - Ship A

The chart for the channel transits on Ship A is shown in Figure 3-41. The

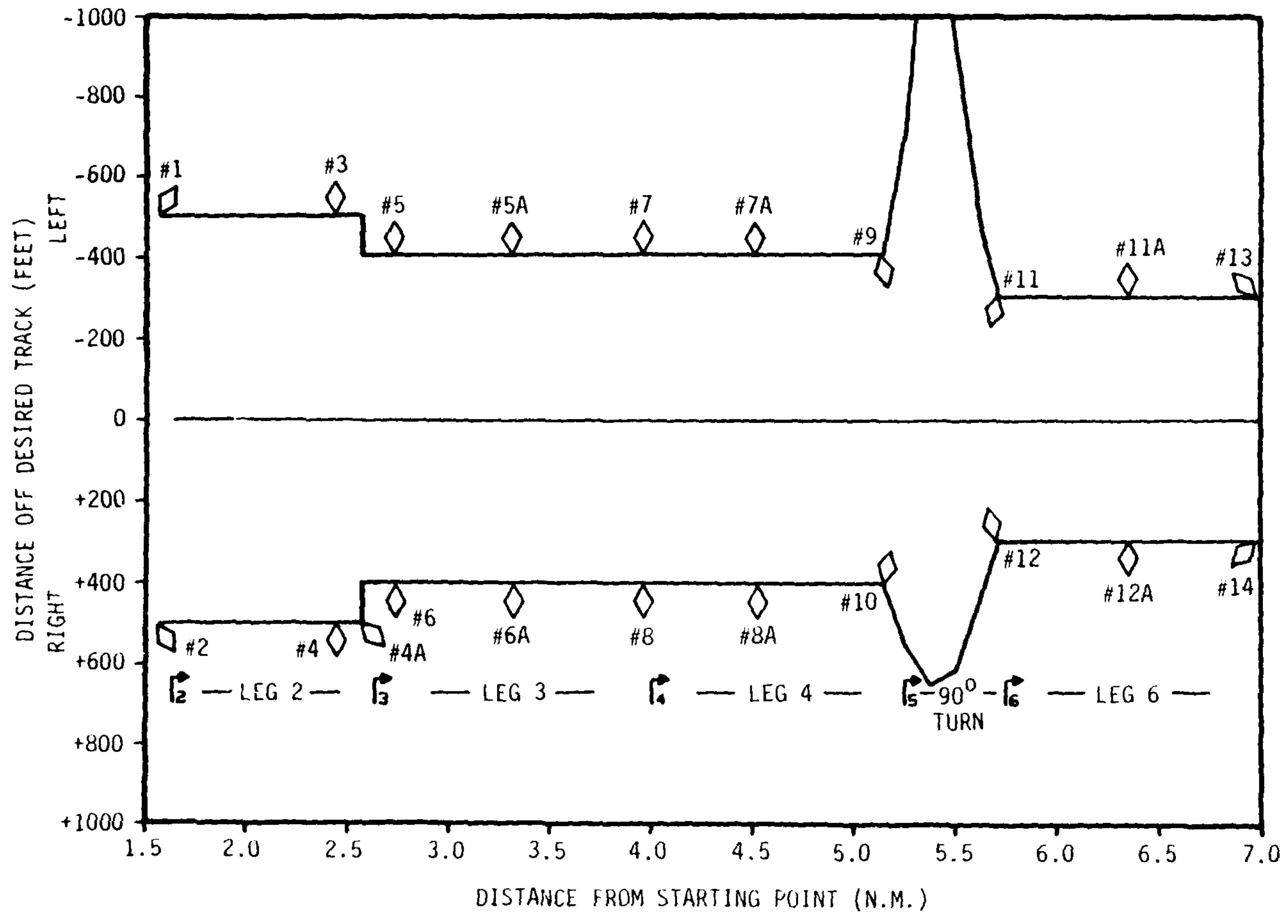


Figure 3-40. Summary Ground Track Basic Chart

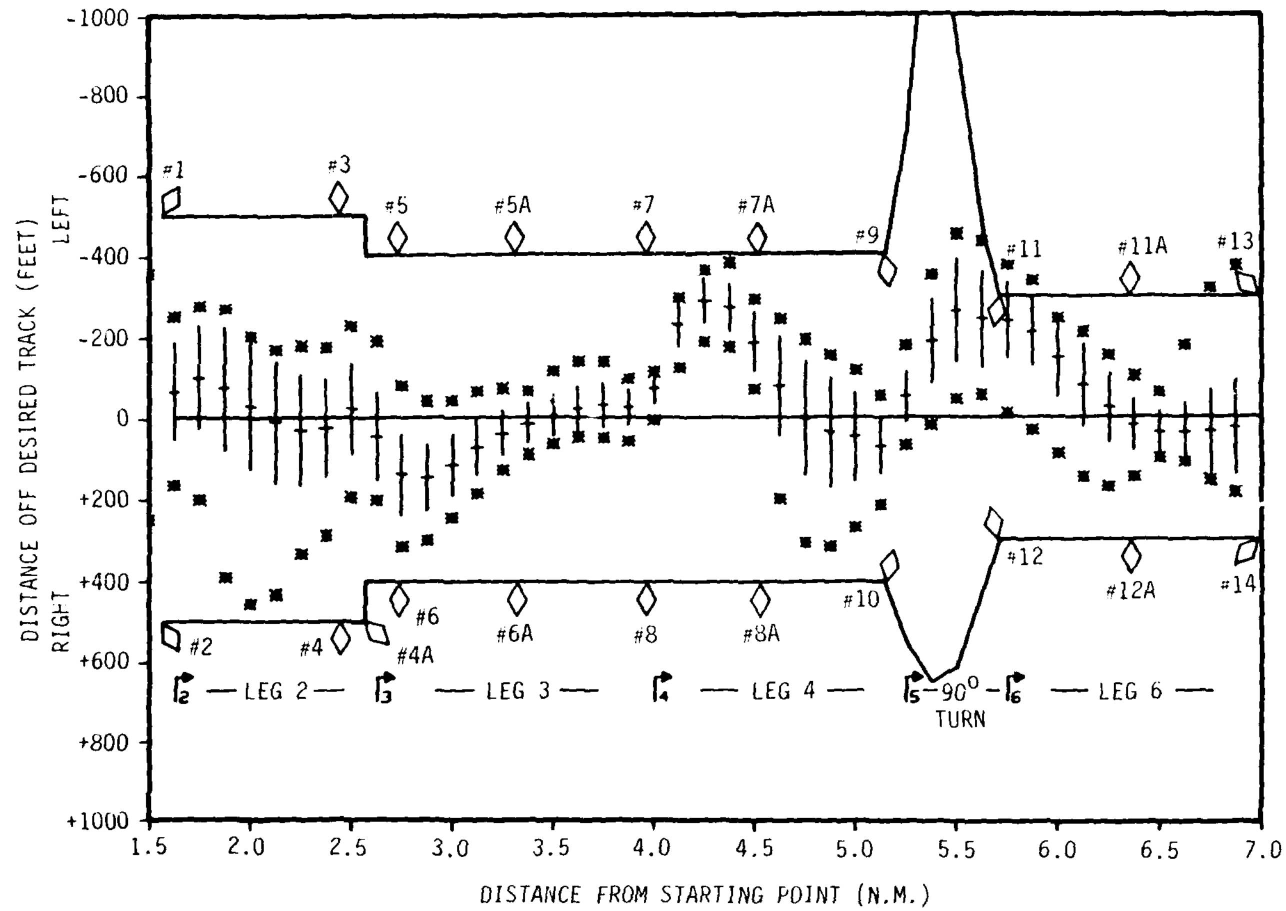


Figure 3-41. Summary Ground Track Ship A

sixteen subject average off-track deviation in leg 2 was never larger than 80 feet, although the largest one sigma (that is, variability) was twice that value and the center of gravity (CG) for one pilot on the A ship was located approximately 25 feet from the starboard channel boundary. This latter difficulty occurred approximately half way through the leg.

On average the performance in leg 3 was superior to that of leg 2 and the average off-track deviation, one sigma, and maximum and minimum values were quite small just prior to the starboard 25° turn between legs 3 and 4. The effect of the starboard turn caused the average off-track deviation to build to almost 300 feet to the left of the centerline (in leg 4) with one pilot's ship CG practically touching the channel boundary. The skin of the ship did actually penetrate the port boundary line at this point. On average, the pilots recovered after the 25° starboard turn and then tended to move again to the left of the desired course line in the 90° turn (leg 5). The entrance to the 600 foot leg shows that the average off-track deviation of the CG for Ship A was within 50 feet of the channel boundary, with the largest value of this measure, for one of the pilots, falling well beyond the channel limit. The pilots recovered in the remainder of leg 6 as they slowed their vessels towards the desired end of track speed, except for one pilot who again lost control and went outside of the channel.

3.3.2 Summary Track - Ship B

The summary chart for channel transits on Ship B is shown in Figure 3-42. The 16 subject average off-track deviation in leg 2 was never more than 100 feet and the largest one sigma was approximately 175 feet. The CG of all Ship B transits in leg 2 was never closer to the boundary limit than 140 feet. The 16 subject average at the start of leg 3 was slightly under 100 feet to starboard and completion of the leg shows the average practically on track. The 25° starboard turn at the start of leg 4 caused an average off-track deviation build up to approximately 200 feet, with one pilot bringing his vessel's CG within 50 feet of the boundary and causing the ship itself to actually penetrate the boundary limit. On average, channel position recovery occurred after that point in leg 4 and never exceeded 100 feet in the remainder of the channel. Towards the end of the 90° turn there again was penetration of the port channel limit line and the variability between pilots did build to a one sigma of approximately 150'. The final leg showed a slow average movement to starboard from approximately 100 feet to the left to 50 feet to the right of the desired track line.

3.3.3 Summary Track - Ship C and Ship E

The chart for the channel transit on Ship C is shown in Figure 3-43.

The 16 subject average off-track deviation for Ship C was never more than 125 feet in any portion of the transit including leg 2, the start of leg 4 and the 90° turn. The variability of the group was never more than 150 feet (one sigma) except at the entrance to leg 2. It was also at that position that one pilot penetrated the port boundary. No one exceeded the boundary limits at the start of the leg 6, i.e., at the completion of the 90° turn, while conning this vessel.

A similar series of comments are

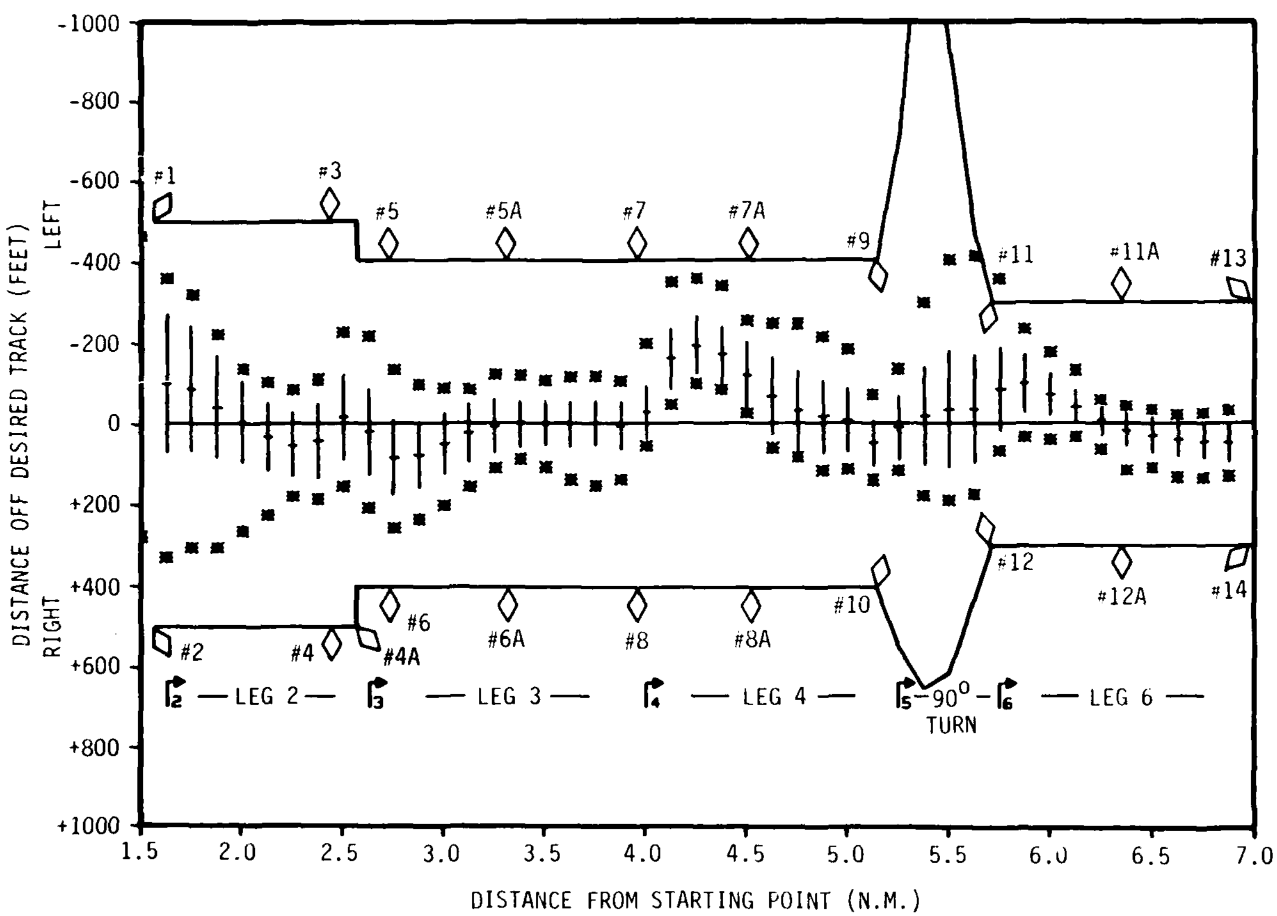


Figure 3-42. Summary Ground Track Ship B

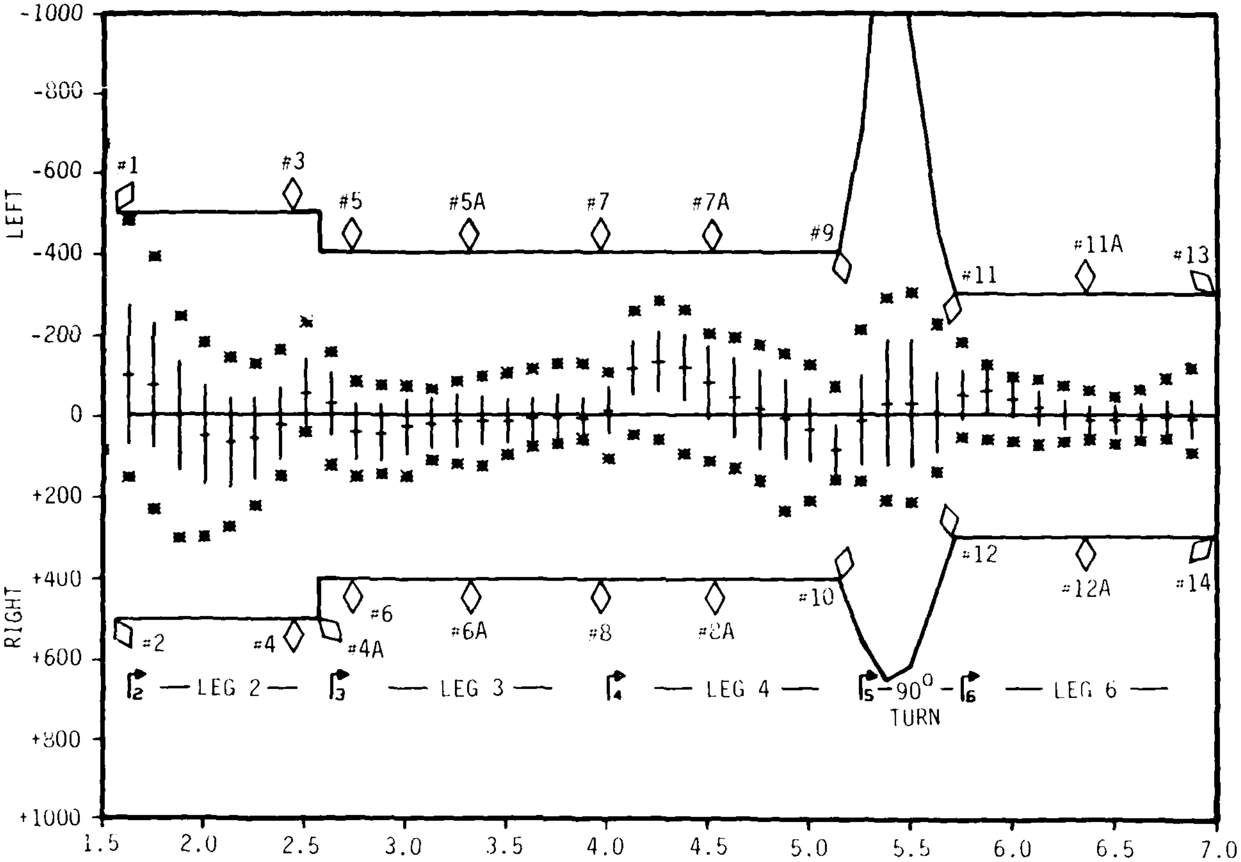


Figure 3-43. Summary Ground Track Ship C

applicable to the results for performance that was demonstrated on Ship E, shown in the summary track of Figure 3-44. Except for the start of leg 2, performance on the more stable vessel indicated small average off-track deviations (less than 100 feet), no boundary penetrations, and a maximum variability under 150 feet. The maximum and minimum values of off-track deviation were smallest for Ship E, compared with all other ships for leg 3, 4, 5 and 6, and smaller than Ship A and Ship C, for leg 2.

3.3.4 Summary Track - Conclusions

The results shown in Figures 3-41 through 3-44 display the same data that were used for the statistical analyses discussed earlier. However this graphical presentation gives more insight into the transits and variations that occurred within the legs themselves. As discussed under the Pilot Difficulty measure (section 3.2.2) it is apparent that the pilots, in general, had the most difficulty with the start of leg 2, the start of leg 4 (the 25° starboard turn) and the pullout from the 90° turn at the start of leg 6. It appears that at least one pilot on each of the ships had difficulty with the channel entrance, most probably caused by the shear current outside of the channel. Other than that, differences in the average performance on the four vessels were quite apparent with the "poorest" overall performance on Ship A and "best" on Ship E. Performance on Ship B was somewhat better, overall, than on Ship A, and Ship C was slightly poorer than with Ship E. The ordering of performance that is evidenced by the four graphs clearly shows the effects of stability on performance under the conditions that were imposed. The most unstable vessel (A) caused variable and, at some points, somewhat uncontrolled performance by the pilots, while the most stable ship (E) allowed them to transit the channel in an orderly manner.

3.4 PILOT POPULATION PARAMETER ESTIMATIONS

A previous Section 3.2 presented the performance findings for a sample group of pilots that transited the "ABC" Harbor under moderate environmental conditions of wind and current. The data were grouped in accordance with the vessel that was conned and statistical comparisons were made between the piloted performance on the different ships. Inferences were then drawn regarding the controllability difficulties that were imposed by the differences in the inherent maneuverability characteristics of the four ships that were investigated.

The sixteen pilots in the sample were randomly selected and were representatives of the parent population from which they were drawn; namely, pilot organizations with personnel experienced on tankers with a displacement of at least 80,000 DWT. It is, of course, desirable to extrapolate from the sample group to the parent population itself. The experimental data were therefore subjected to additional analyses which allowed further inferences to be made. These were based not so much on sample group data to sample group data comparisons for the different ships, but on comparisons relative to the population from which the test subject sample was drawn. By statistical manipulation of the available data, estimations were made of the parent population, with regard to various performance measures.

Within a given probability of error estimations were made for *all* exper-

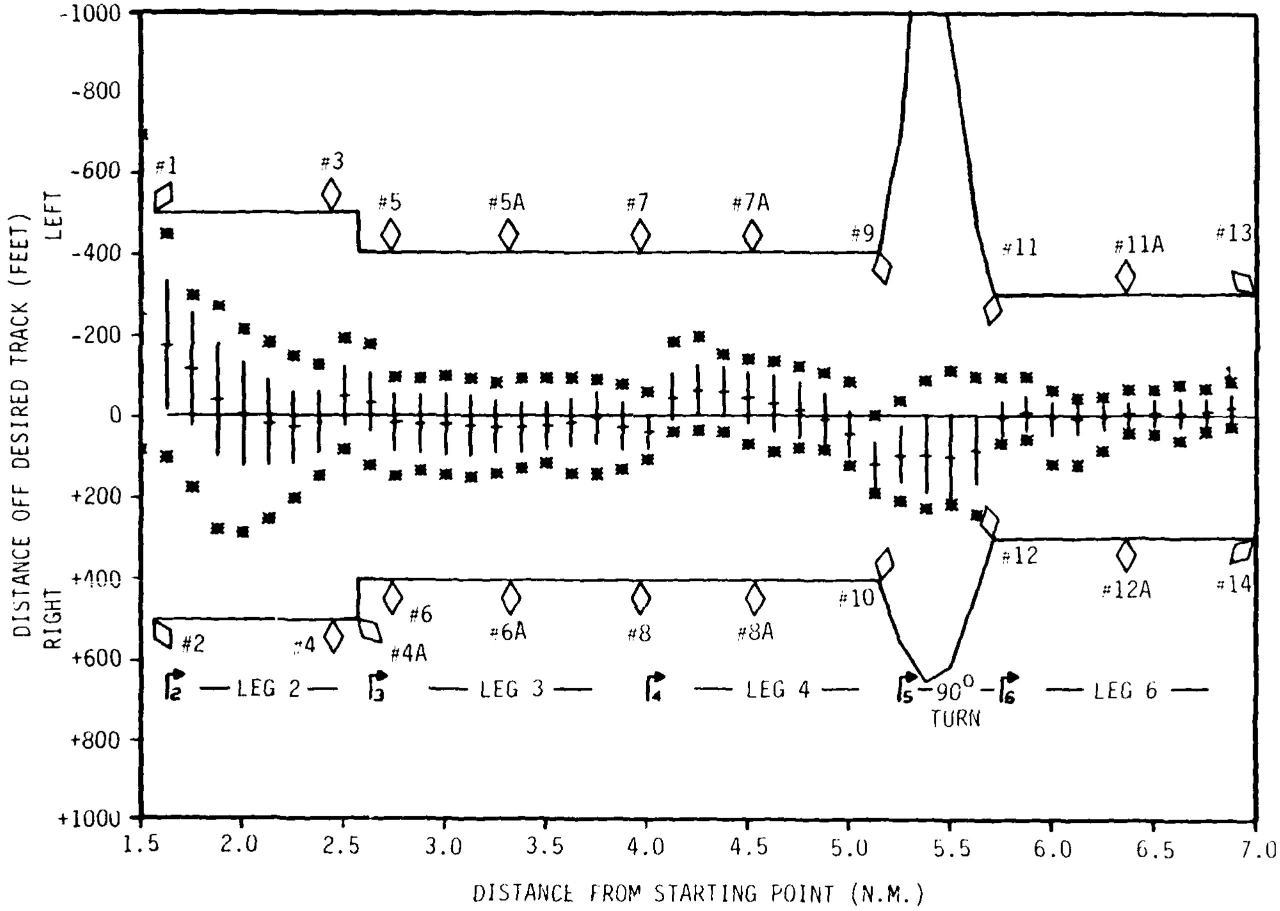


Figure 3-44. Summary Ground Track Ship E

ienced pilots who might transit this type of channel under similar environmental conditions and on similar ships. By studying the composite parent population parameters obtained in this manner, further inferences were possible regarding the effects of the variability in ship stability on the transiting performance. The performance measures that were used for these estimations were Root Mean Square Off Track Deviation (X_{RMS}) and Consistency (variability) of ship track around the average track of the passage (X_{σ}). Estimations of the range of the population means were calculated from the sample statistics and took the form of confidence intervals; that is, the interval in the distribution of the performance measure within which the population mean (μ) would be expected to be found, at a 95% confidence level.

The estimation of the range of values of μ for the RMS of Off-Track Deviation (X_{RMS}) is presented in graphical form in Figure 3-45 through Figure 3-50 for both the total transit and for each of the five individual legs. The data are presented in more complete tabular form for this measure, as well as all measures discussed in this section, in Appendix C, Table C-18.

For the total overall channel the upper limit of the 95% confidence interval for μ of X_{RMS} for Ship A is 174 feet while for the other three vessels it is approximately 100 feet. The lower limit, or "lowest" average for Ship A is 143 feet and approximately 75 feet for the other vessels. Analyses of the data for the individual legs indicate that the interval for Ship A is either centered at approximately the same value as the other three vessels for legs 2 and 3 or is larger, as in leg 4, the 90° turn and leg 6.

A somewhat similar situation is in evidence when consistency or variability around the mean track line is considered, as in Figure 3-51 through 3-56. For the total channel (Figure 3-51) the 95% confidence interval of Consistency has an upper limit of 158 feet for Ship A and 107, 92 and 84 feet for Ships B, C and E respectively. The lower limit for Ship A is 123 feet while for the other three vessels it is approximately 75 feet. Examination of the findings for the individual legs again shows that the probable consistency interval for Ship A in leg 4, the 90° turn and leg 6 is centered at a higher level than for the other three vessels.

These estimations for most probable results that would be found in the total population again reflect that Ship A causes pilots more ship handling difficulties than do the other ships, as measured by the RMS of Off-Track Deviation as well as the variability of the off track deviation around the average value. These overall differences were most pronounced in the two legs containing the starboard turn, as well as the leg which required unaided slowing down of ownship speed, leg 6.

3.5 SUBJECTIVE FINDINGS

As indicated in paragraph 2.6.3, a final debriefing was held with each test subject at the conclusion of his data runs to assess the subject's reactions to the experiment, vessel handling qualitites, as well as similarities of the experimental runs to actual experience. Figure 2-10 contains the structured format that was used for this purpose. A summary and discussion of the subjective findings that were obtained from this sample grouping of pilots is contained below.

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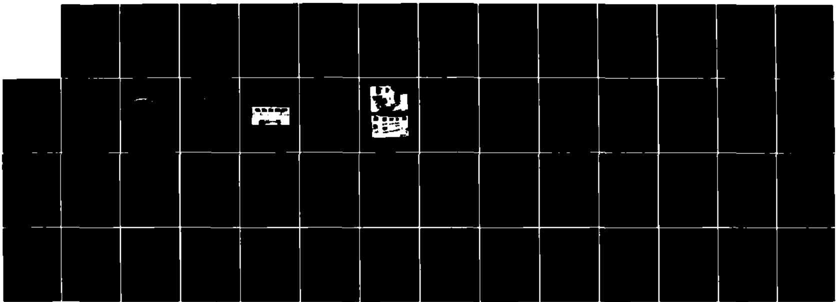

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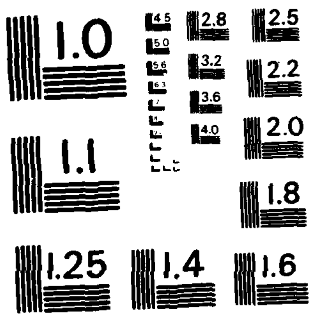

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

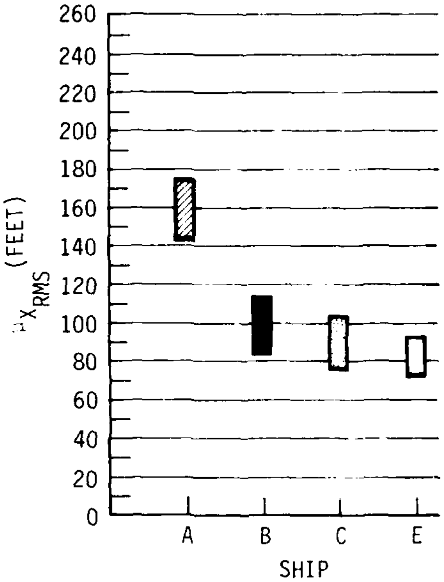

Figure 3-45. Confidence Interval of Population Mean (95%) Total Channel - X_{RMS} vs. Ship Type

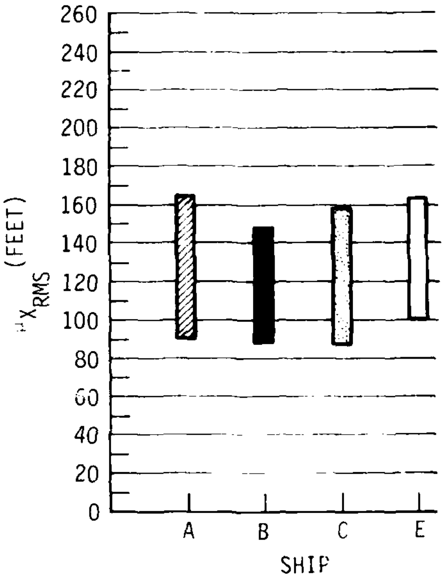

Figure 3-46. Confidence Interval of Population Mean (95%) Leg 2 - X_{RMS} vs. Ship Type

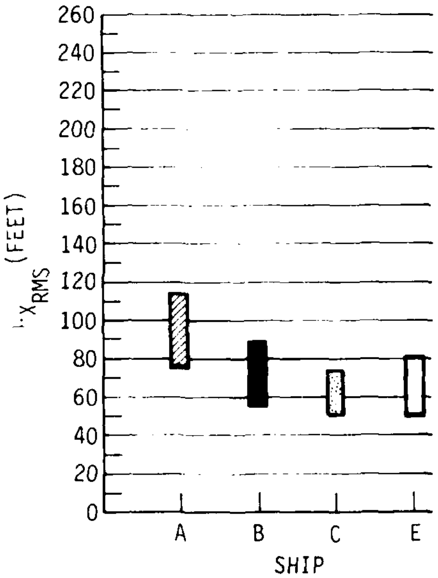

Figure 3-47. Confidence Interval of Population Mean (95%) Leg 3 - X_{RMS} vs. Ship Type

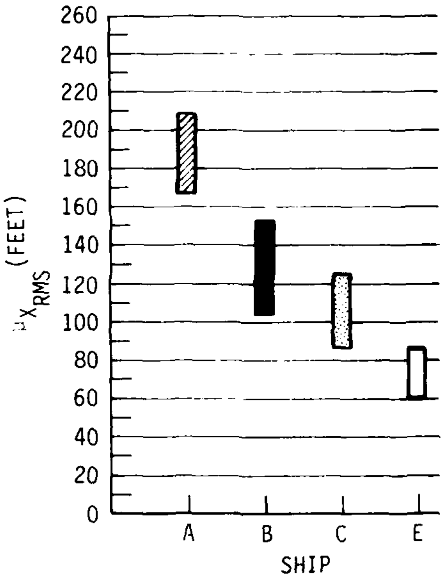

Figure 3-48. Confidence Interval of Population Mean (95%) Leg 4 - X_{RMS} vs. Ship Type

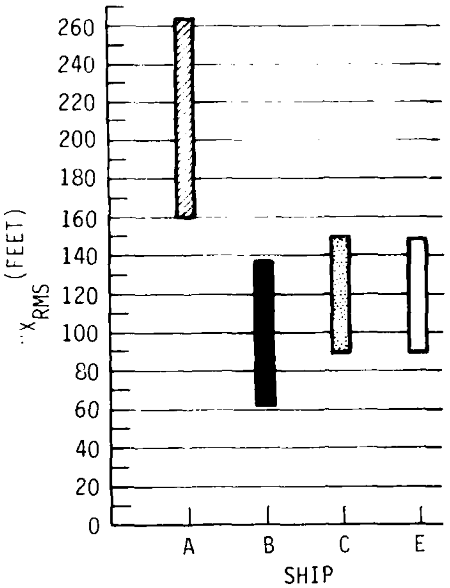

Figure 3-49. Confidence Interval of Population Mean (95%) 90^{o} Turn - X_{RMS} vs. Ship Type

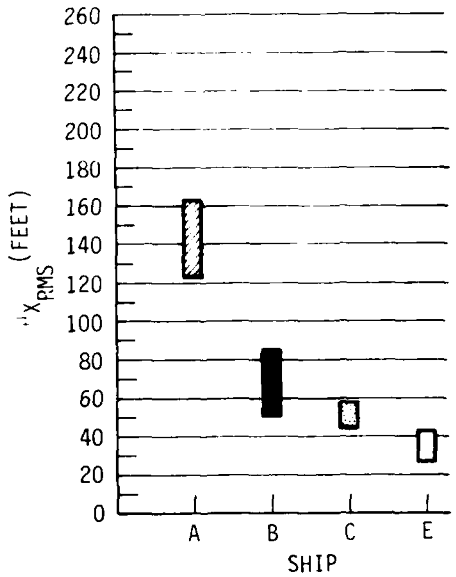

Figure 3-50. Confidence Interval of Population Mean (95%) Leg 6 - X_{RMS} vs. Ship Type

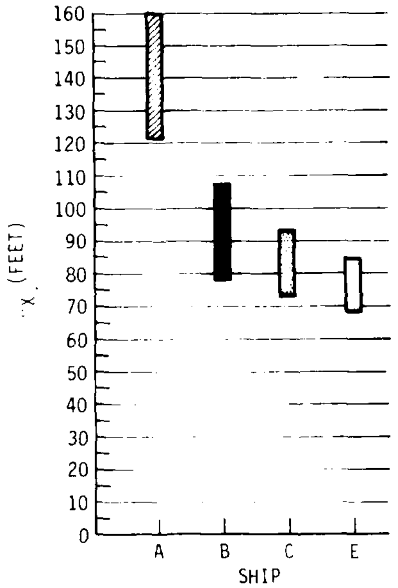

Figure 3-51. Confidence Interval of Population Mean (95%) Total Channel - Consistency (X_σ) vs. Ship Type

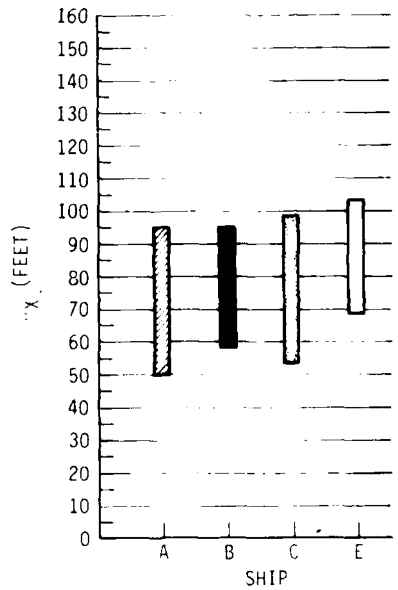

Figure 3-52. Confidence Interval of Population Mean (95%) Leg 2 - Consistency (X_σ) vs. Ship Type

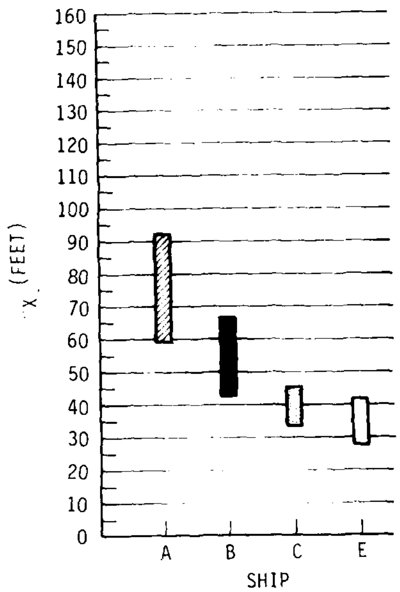

Figure 3-53. Confidence Interval of Population Mean (95%) Leg 3 - Consistency (X_σ) vs. Ship Type

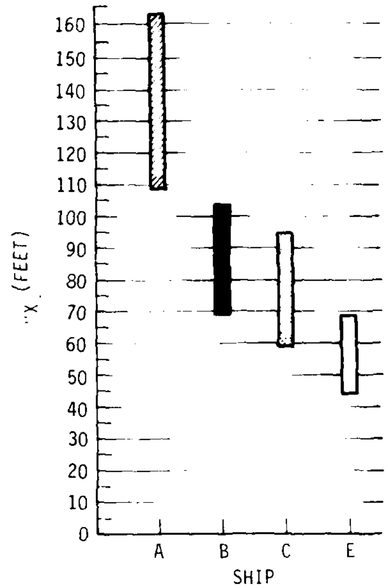

Figure 3-54. Confidence Interval of Population Mean (95%) Leg 4 - Consistency (X_σ) vs. Ship Type

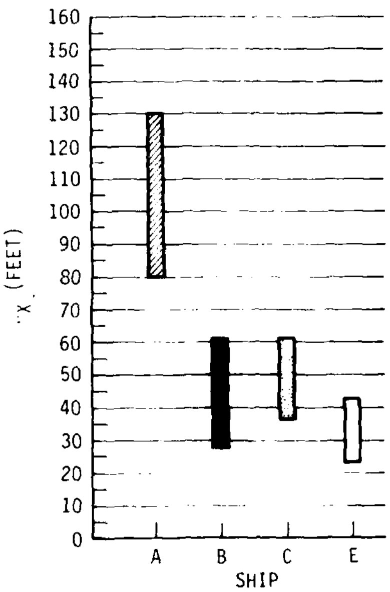

Figure 3-55. Confidence Interval of Population Mean (95%) 90^o Turn - Consistency (X_σ) vs. Ship Type

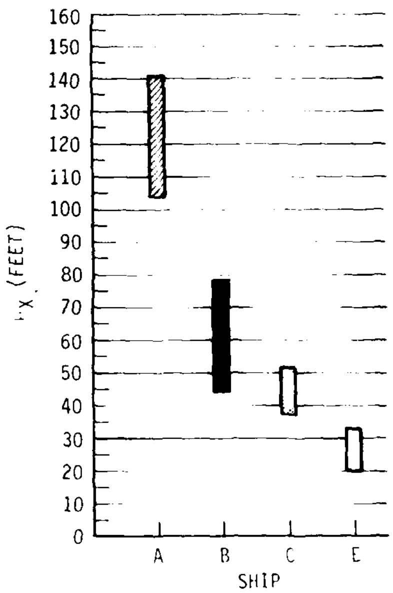

Figure 3-56. Confidence Interval of Population Mean (95%) Leg 6 - Consistency (X_σ) vs. Ship Type

3.5.1 Subject Maneuvering Difficulty

The subjects were asked to give their impressions of ship ranking based on the difficulty that they had experienced with the four vessels; one for the ship that was most difficult to handle, through four for the easiest. A score was then established for each ranking in accordance with Table 3-4.

It can be seen that several classes of "tied" rankings existed between ranks 2, 3 and 4 and the scoring was established so that each subject would contribute a total score of 20 under any condition of rank distributions. For example, if a pilot thought that A was most difficult (rank 1, score 8), C was moderately difficult (rank 2, score 6) and C and E were equally difficult for rank 3 and 4 (each ranked at 3.5, each scored 3), then the total pilot score would be 20. The scoring was based on a maximum score of 128, if all 16 subjects had felt that the same ship was most difficult (16 x 8), and a score of 32 if they all felt that the same ship was easiest (16 x 2). By this scoring system the results were that Ship A received a total score of 120, Ship B (74), Ship C (66) and Ship E (60).

Fourteen of the sixteen subjects found Ship A the most difficult to handle while twelve subjects ranked Ship E as moderately easy, easiest or tied with another vessel for these two lowest rankings (i.e., a score of 3). Eleven subjects felt that Ship B was neither hardest nor easiest while twelve subjects evaluated Ship C in that intermediate position.

By composite scoring of each ship, as well as individual frequency counts, it can be seen that the pilots' subjective evaluations of inherent maneuvering capabilities of the different ships parallel the stability criteria of the vessels; the most unstable ship (A) was thought to be the most difficult to handle while the most stable (E) was found to be the easiest. Ships B and C fell between these extremes and completed the ordering parallelism of A followed by B followed by C and lastly, E.

3.5.2 Desired Course Line

There is always the possibility that the experimental conditions that are imposed by a researcher conducting a

TABLE 3-4 DIFFICULTY RANK VS. SCORE

Rank	Comment	Score
1	o Most Difficult	8
	o No Difference Between Vessels Ranked as 1 & 2	7
2	o Moderately Difficult	6
	o No Difference Between Vessels Ranked as 2 & 3	5
3	o Moderately Easy	4
	o No Difference Between Vessels Ranked as 2, 3 & 4	3
4	o Easiest	2

simulator experiment force the test subjects to react in an abnormal manner; that is, contrary to the methods they would normally use on a real ship. The second question posed in the final debriefing therefore addressed the issue of the desired track line that was used for the test scenario. The subjects were asked if they normally would have selected the centerline desired track line, under no traffic conditions.

Of the sixteen subjects, fourteen indicated they would have selected the track line that was prescribed under clear visibility, no traffic conditions. However, many of these pilots would have "favored" one side of the channel or the other, at the turns. Two of the sixteen indicated that they would have "favored" one side or the other throughout the channel, with the wind most often being the determining factor. It appears that the centerline restriction was not considered to be unrealistic or cause for concern with the pilots, and therefore did not have a detrimental effect on the experimental findings. Fourteen of the pilots indicated that they would have followed the path, and examination of the individual track plots for the other two pilots showed that they also attempted to follow the directive.

3.5.3 Task Realism

The sixteen test subjects were drawn from four pilot associations; nine from Group I, one from Group II, four from Group III and two from Group IV. During the final debriefing, each was asked a dual question concerning the overall task, i.e., "Was the task realistic and how did the "ABC" Harbor channel requirements compare with those found in the home area?" All sixteen pilots used as test subjects felt that the overall experiment task was realistic, except that two of them felt that the most unstable vessel (Ship A) would not normally be brought unaided into a harbor without the use of tugs.

The Group I pilots felt that the "ABC" Harbor offered no surprises/difficulties as far as channel widths were concerned but that the 90° turn and shear current at the entrance were more difficult than conditions found in their home area. The test subjects from Group III felt that various portions of their normal working area contained comparable channel widths and bends. One test subject in this group mentioned that the cross set at the entrance to the "ABC" harbor was higher than in his home area.

The two pilot grouping (IV) found that the channel was both realistic and similar to their home area in all respects except that bank suction was not present in the "ABC" harbor, and is a factor in their home area. The single pilot (Group II) indicated that his home area contained sections with comparable currents, sets, turns, and channel widths, and that the simulated scenario was realistic.

These subjective pilot reactions confirm that the desired goals were reached in the experimental use of this harbor. Overall, the pilots felt that the task was realistic and that they were not "overwhelmed" by totally unfamiliar channel conditions. The size of the cross current set in the approach phase appeared to be the most significant area of difference with prior experience. This segment was not used in the analyses of performance difficulty that were conducted for the experiment, since the first leg was actually a ship familiarization phase.

3.5.4 Suggested Experimental Task Changes

The question relating to suggestions for changes to the basic task, to bring out differences in ship inherent maneuvering characteristics better, probably received the poorest set of responses. The most relevent suggestions were concerned with constraining conditions caused by traffic and/or proximity to an anchorage or other close quarter situations. Actually, during the design of the experimental conditions it was felt that the variable channel width (from 1000 feet to 600 feet) would have the same type of constraining influence on pilot behavior as natural impediments and traffic would. Bank suction was also considered at that time but it was decided that it should not be employed since it might influence pilots' techniques for turns, as well as their willingness to follow the requested center line desired track. In point of fact, the two pilots who discussed this issue (paragraph 3.5.3) most assuredly would have used the banks as an aid at the turns, with resulting detrimental effects on the averages of the major performance measures related to off-track deviation.

3.5.5 Difficult Ships

The experiment reported herein was concerned with the ability of experienced pilots to overcome the variability in inherent maneuvering characteristics of a set of ships that differed primarily with regard to their stability. The pilots that were used in this experiment encounter a great variety of ships in the execution of their normal responsibilities and have come to recognize certain ship/ship classes as "most difficult to handle." The last question that was posed to each of the test subjects attempted to see if a consensus existed among these mariners (from different pilotage areas) as to whether or not there was a common source of difficulty that was experienced by all of them. Interestingly, the Society of Naval Architects and Marine Engineers, H-10 Panel (Ship Controllability) is also following this line of inquiry and has sent 73 questionnaires to various River & Harbor Piloting Associations which delve into the problem of which functional characteristic causes the greatest ship handling difficulties. An interim return of results (38) has been reported at a February 1982 meeting of the panel.[4]

A summary of the findings that were developed from the sixteen test subjects during the final debriefings is illustrated in Table 3-5. The findings have been grouped into four categories: Equipment, Engine Power, Rudder Capabilities and Miscellaneous. The number of subjects who responded in each instance is also appropriately listed. It should be noted that this question was presented to the subjects in an open ended manner, e.g., "What characteristics make one vessel more difficult to handle than another," rather than "Which of the following list of characteristics do you feel contribute to a poor handling ship designation?" The former method was used so as not to influence the pilots, but the results were somewhat varied with some test subjects not even considering items that immediately occurred to other pilots.

The interim results of the SNAME questionnaire reflect very similar feelings among those involved with many different types of vessels. More than 50% of the 78 mailings were returned at the time of the reference

TABLE 3-5. CHARACTERISTICS CAUSES OF SHIP HANDLING DIFFICULTIES

Characteristics of Subjects	Number
o EQUIPMENT:	
Reliability of equipment (age & initial design)	1
Layout of instrumentation as well as equipment available	1
o LOW ENGINE POWER:	
Poor acceleration of ship speed	3
Engine response	2
Backing poorly	4
Inability to go slowly with hard over rudder and not stall engine (diesel)	1
o RUDDER CAPABILITIES:	
Small size	8
Jumboized ships without rudder change	1
Small rudder reserve because of the continual need for large rudder angles	1
Poor swing checking ability	4
Poor steering	1
Not responsive to helm (stable, small rudder)	3
Quick build up of turn rates in turns	1
Slow rudder movement because of undersized rudder engine	3
o MISCELLANEOUS:	
Predictability	1
Lack of response	1
Short, beamy ships suck against banks more than long, lean ships	1
Trimmed poorly	1
Trimmed down in bow causing poor checking of swing	1
Visibility, i.e., booms, containers, etc.	2

reporting. Of the 38 returns:

- o 34 indicate that the key problem of ships today is the lack of maneuvering control at slow speed.
- o 27 say the slow response or lack of response to engine or rudder.
- o 24 say the lack of straight-line stopping ability.
- o 22 say the lack of swing control with moderate rudder angles.

Although both the CAORF findings, as well as the SNAME results are somewhat varied (within, as well as between the two) a strong undercurrent of feeling exists in the area of rudder response, swing control, checking capabilities, etc. It is just this set of capabilities which was used to establish differences between the four ships employed in the *experiment* — Ship A being highly unstable through Ship E, the most stable.

CHAPTER 4

SUMMARY DISCUSSION AND CONCLUSIONS

4.1 INTRODUCTION

The Maneuvering Response Experiment was established to examine the differences in ship handling performance of pilots transiting a narrow waterway on ships that exhibit distinctly different inherent maneuvering characteristics. The experiment had three explicit objectives, and one that was implied.

Explicitly, the experiment attempted to:

- Determine the variations in ship handling performance which are attributable to differences in vessel inherent maneuvering characteristics, under conditions imposed by narrow channel transits.
- Determine the impact on pilots' workload which is caused by the transit conditions and ship's characteristics.
- Determine the pilots' perceptions of the ship handling difficulties which have been caused by the transit conditions as well as the inherent maneuvering characteristics of the vessels.

The implicit objective of the experiment is common to all CAORF investigations; namely, to structure an experimental design with sufficient controlling conditions so as to ensure that the explicit objectives are met with a minimum level of confounding influences.

4.2 SHIP HANDLING

There were four vessels that were compared in the experiment, with inherent maneuvering characteristics which varied from stable (Ship E) to unstable (Ship A). Ship C was marginally stable, while the stability of Ship B fell between that of Ship A and Ship C. Various statistical and non-statistical analyses were performed to assess the ship handling difficulties that were imposed on the sample group of pilots by the variability in handling characteristics, resulting in the following overview; Ship A was by far the most difficult ship to handle, causing the most problems, and Ship E was the easiest, allowing the pilots to display the best performance of all. Performance on Ships B and C tended to also fall into an order which correlated with stability, but not to the marked degree as with the other two vessels.

There were three main harbor areas that tended, as designed, to cause the pilots difficulty; namely, the channel entrance (subsequent to a high shear current), a 25° starboard turn (which reinforced a starboard beam wind), and a 90° starboard turn (with a following current and a wind which changed from starboard beam to slightly off the bow).

The statistical analyses that are functions of distance off desired track contributed heavily to the overview noted above. Average off-track deviation ($\bar{X}$) and X_{RMS}, as well as consistency of track (X_{σ}), all indicated

poorer performances on Ship A, and better performances on Ship E, especially in the legs which had been designed with the most difficult ship handling problems. Swept path, or the area which is "carved out" of the channel by the extremities of the ship, was wider for Ship A than for the other vessels. This performance trend was also observed for the measure of Boundary Penetrations, with the more unstable vessel tending to "side slip" at the turning areas of difficulty at a higher incident rate, and therefore more frequently moving out of the channel boundary limits.

A correlation analysis of performance difficulty with ship stability was also performed and the findings indicated that the ship handling displayed by half the sample correlated strongly with ship stability, i.e., at a level of +0.950 or higher. The average correlation for the total group was +0.813, also quite strong.

Summary ground tracks for each ship, which averaged the performance of all the pilots on each of the ships, were also developed and indicated the difficulty levels encountered at the three specific areas, previously noted. The most unstable vessel (A) caused variable and, at some points, somewhat uncontrolled performance by the pilots, while the most stable ship (E) allowed them to transit the channel in an orderly manner.

4.3 PILOT WORKLOAD

The impact on pilot workload, caused by the transit conditions and inherent ship maneuvering characteristics, showed little to no effect. The findings indicate that there was either no relationship between workload and ship stability, or, that the parameters selected to measure this effect were inadequate or *insensitive* to the task. Judging by the numerous Boundary Penetrations that were in evidence, as well as the relationship of Boundary Penetrations to ship maneuvering capabilities, it would appear that there should have been a strong pilot-ship workload effect. The workload parameter *did* show a leg effect, which indicated increased pilot commands in the channel entrance leg and the 90° turn. This, however, occurred independently of the ship that was being conned.

4.4 PILOT PERCEPTIONS

Various performance measures and analyses *did* indicate that the ship handling characteristics of the sample pilot grouping varied, and that they were dependent on the stability/inherent maneuvering characteristics of the vessel being conned. To assure that the pilots were aware of their difficulties (and therefore presumably attempting to better their performance when they were having more difficulty), they were asked to subjectively rank the ships according to difficulty, after they completed their last data run. This information was analysed at the conclusion of the experiment and showed that the pilots were well aware of performance problems, showing a high positive correlation of perceived difficulty with the performance difficulties actually displayed. A high positive correlation of perception with the inherent maneuvering characteristics of the ships themselves was also found. Fourteen of the sixteen subjects found Ship A to be the most difficult to handle while twelve ranked Ship E as moderately easy, easiest, or tied with another vessel for these lowest rankings. Approximately three-quarters of the group ranked Ships B and C as neither hardest nor easiest to handle.

4.5 EXPERIMENTAL VALIDITY

During the early phases of the project every effort was made to structure the experimental conditions so that the explicit objectives of the experiment could be validly met. It was also decided, at that time, to question the test subjects during their final debriefings in an attempt to ascertain whether confounding influences (e.g., unrealistic requirements) existed. One question was posed to the pilots concerning the overall realism of the experimental task, a second was concerned with the desired track line that was used, and a third concerned itself with suggestions regarding additional tasks which might have brought out ship handling characteristics in a superior manner. Responses to all three of these questions were positive; that is, the overall task was realistic, similar in general to home harbor conditions, the center line desired track was adequate, and no obvious need was expressed for meaningful changes to the experimental tasks.

By far the most significant finding was with respect to the number of runs which were required of each test subject, as well as whether or not two channel familiarization runs were adequate to familiarize the pilots with the experimental tasks that were to be performed on the simulator. The Run-Order analyses were conducted to ascertain if any effects could be discerned related to the order in which the ships were run. This would have indicated either fatigue effects or simulator learning effects. The results of the Run-Order analyses indicated the soundness of the experiment design. Essentially, none of the key performance measures showed a run-order effect compared with practically all of them showing a ship effect.

The implications of these findings indicate that confounding influences were minimized by the structure and conditions of the experiment design.

4.6 CONCLUSIONS

As indicated earlier in this report, the basic question that this experiment has attempted to explore is concerned with a facet of "Pilot Lore." When asked about potential problems concerning the process by which they become familiar with vessels that they have not sailed before, experienced pilots commonly express the view that they can get the "feel" of a new ship very quickly after taking the conn. This "feel" is concerned with the ability to handle the vessel safely throughout the pilotage area and implies that the level of this acquired ability does not substantively vary for any ship that they may be required to pilot. The fact that this is accomplished in an efficient, professional manner is evidenced by statistics related to the high level of safe passages that *do* occur every year, under highly variable conditions. A question has therefore existed regarding the variability of this familiarization ability and the manner in which different vessels and different pilots affect the man/ship interaction which is displayed.

The experiment has shown that piloted performance on ships having different inherent maneuvering characteristics *is* variable, with the resulting performance on the more unstable vessel being poorer than on the marginally stable or stable ships. The pilots are aware that they are having more difficulty with the unstable ships but still display significantly different transit performance on them. It can therefore be inferred that this is happening in spite of their recognition of the

situation and their attempts at alleviating the problem difficulties. Because of this, it is obvious that numerous harbor safety implications exist regarding the inherent maneuvering characteristics of existing and new ship designs.

Another interesting conclusion that can be drawn from this program is that the experiment has indicated the beginnings of a standard procedure that can be used to compare relative pilot ship handling capabilities on vessels with differing inherent maneuvering characteristics; with both existing vessels and, perhaps more importantly, new ship designs. A performance data base can be amassed, starting with the data obtained from this experiment, so that other vessels can be used on the simulator in conjunction with additional pilots making additional experimental runs through the test scenario of the "ABC" Harbor. Subsequent analyses of the new data will allow the newer vessel to be ranked relative to the existing ships in the data base. This can be accomplished even prior to the actual construction of a new vessel, and is solely dependent on the generation of the necessary ship coefficients for use in the simulation of the vessel. Decisions regarding necessary maneuvering characteristics design changes can therefore be made much earlier in the design/construction sequence for new vessels through the use of this proposed procedural standard.

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APPENDIX A

THE COMPUTER AIDED OPERATIONS RESEARCH FACILITY (CAORF)

A.1 DESCRIPTION OF CAORF

CAORF is the sophisticated ship-maneuvering simulator operated by the U.S. Maritime Administration for controlled research into man-ship-environment problems. Controlled experiments, which might require several vessels, cannot be performed readily in the real world and would certainly be ruled out for testing situations that involve potential danger. Such experiments can be performed safely and easily at CAORF. A simplified cutaway of the simulator building is shown in Figure A-1 and the relationships among the major subsystems are illustrated in Figure A-2.

All actions called for by the watch officer on the bridge are fed through a central computer that alters the visual scene and all bridge displays and repeaters in accordance with the calculated dynamic response of ownship and the environmental situation being simulated. CAORF has the capability of simulating any ship, port, or area in the world. The major subsystems are:

- **Wheelhouse,** which contains all equipment and controls needed by the test subject watch officer to maneuver ownship through a scenario, including propulsion and steering controls, navigational equipment and communication gear.

- **Central Data Processor,** which computes the motion of ownship in accordance with its known characteristics, models the behavior of all other traffic ships, and drives the appropriate bridge indicators.

- **Image Generator,** which constructs the computer-generated visual image of the surrounding environment and traffic ships that is projected onto a cylindrical screen for visual realism.

- **Radar Signal Generator,** which synthesizes video signals to stimulate the bridge radars and collision avoidance system for the display of traffic ships and surrounding environment.

- **Control Station,** from which the experiment is started and stopped, traffic ships and environment can be controlled, mechanical failures can be introduced, and external communications with ownship's bridge can be simulated.

- **Human Factors Monitoring Station,** from which unobtrusive observation and video recording of test subject behavior can be carried out by experimental psychologists.

A.2 SIMULATED BRIDGE

The simulated bridge consists of a wheelhouse 20 feet (6.1 m) wide and 14 feet (4.3 m) deep. The equipment on the CAORF bridge is similar to that normally available in the merchant fleet and responds with realistically duplicated time delays and accuracy. The arrangement is based on contemporary bridge design and includes the following equipment:

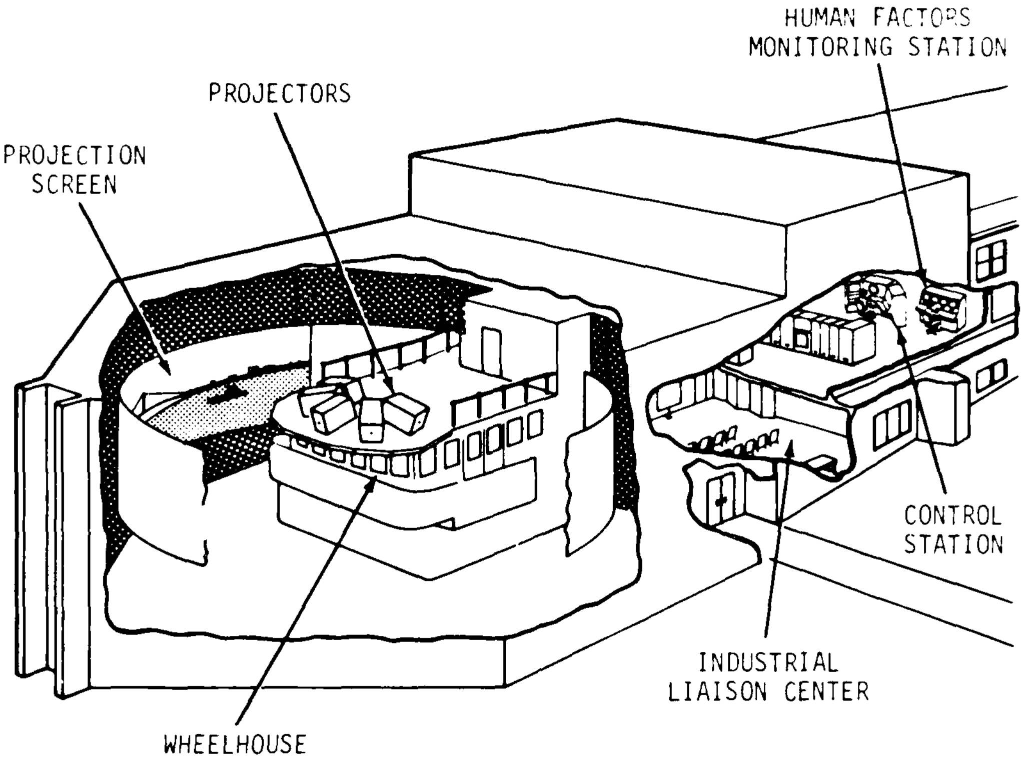

Figure A-1. Cutaway of CAORF Building

- **Steering Controls And Displays** - a gyropilot helm unit with standard steering modes, rate of turn indicator, rudder angle/rudder order indicators, and gyro repeaters.

- **Propulsion Controls and Displays** - an engine control panel (capable of simulating control from either bridge or engine room) containing a combined engine order telegraph/throttle, an rpm indicator and a switch for selecting the operating mode, such as finished with engine, warm up, maneuvering and sea speed.

- **Thruster Controls and Displays** - bow and stern thrusters and their respective indicators and status lights.

- **Navigation Systems** - two radars capable of both relative and true motion presentations, plus a collision avoidance system. Capability exists for future additions such as a digital fathometer, Radio Direction Finder, and Loran C and Omega systems.

- **Communications** - simulated VHF/SSB radio, docking loudspeaker (talkback) system, sound powered phones and ship's whistle.

- **Wind Indicators** - indicate to the bridge crew the true speed and direction of simulated wind.

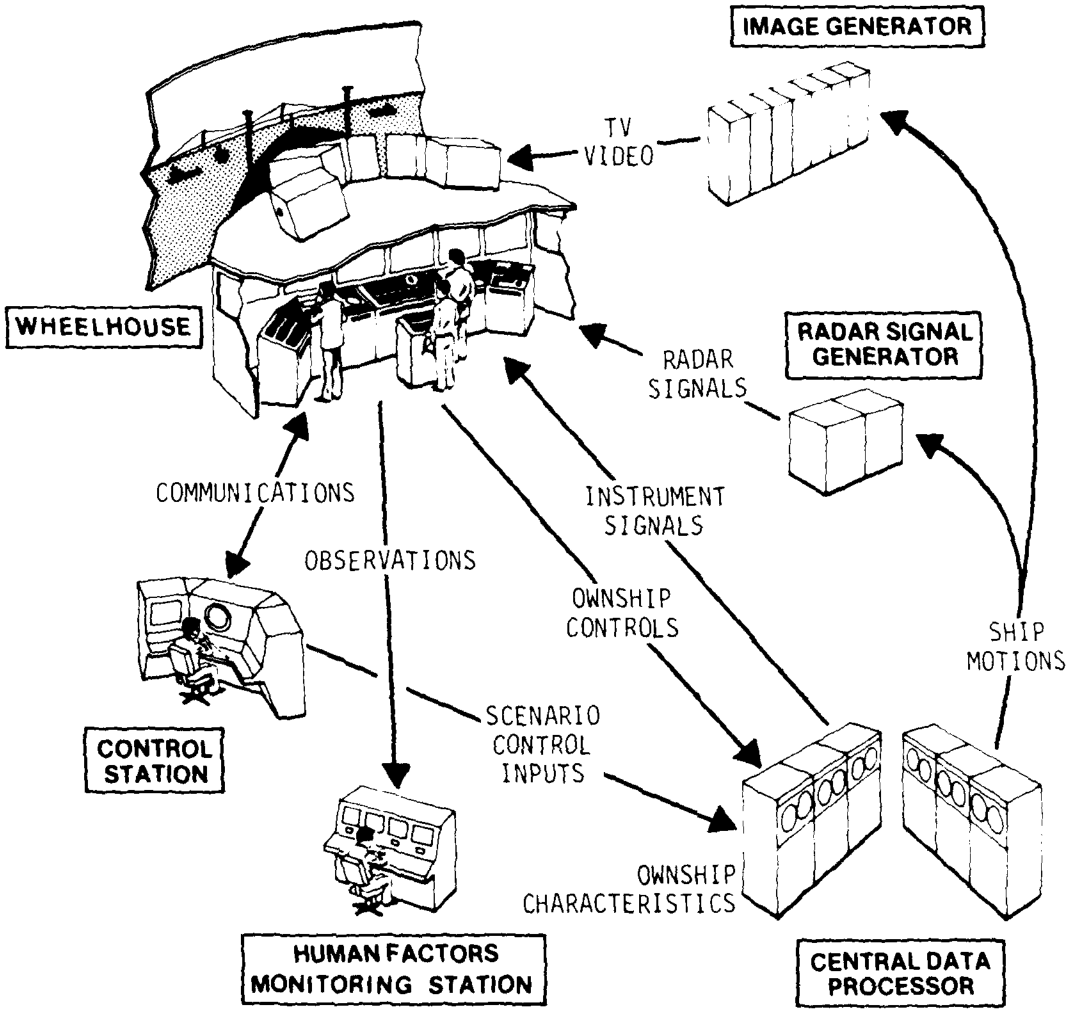

Figure A-2. Major CAORF Subsystems

A.3 OWNSHIP SIMULATION

Any ship can be simulated at CAORF. The computerized equations of motion are adapted to the ship by changing specific coefficients, among which are hydrodynamic, inertial, propulsion, thruster, rudder, aerodynamic, etc. Wind and currents realistically affect ship motion according to draft (loaded or ballasted) and relative speed and direction. Ownship's computer model was validated by comparing various simulated maneuvers (e.g., zig-zag, turning circle, spiral, crash stop, and acceleration tests) with sea trail data.

A.4 IMAGE GENERATION

The visual scene is generated at CAORF to a degree of realism sufficient for valid simulation. The scene (Figure A-3) includes all the man-made structures and natural components of the surrounding scene that mariners familiar with the geographical area deem necessary as cues for navigation.

Thus, bridges, buoys, lighthouses, tall buildings, mountains, glaciers, piers, coastlines, and islands would be depicted in the scene. In addition, the closest traffic ships and the forebody of

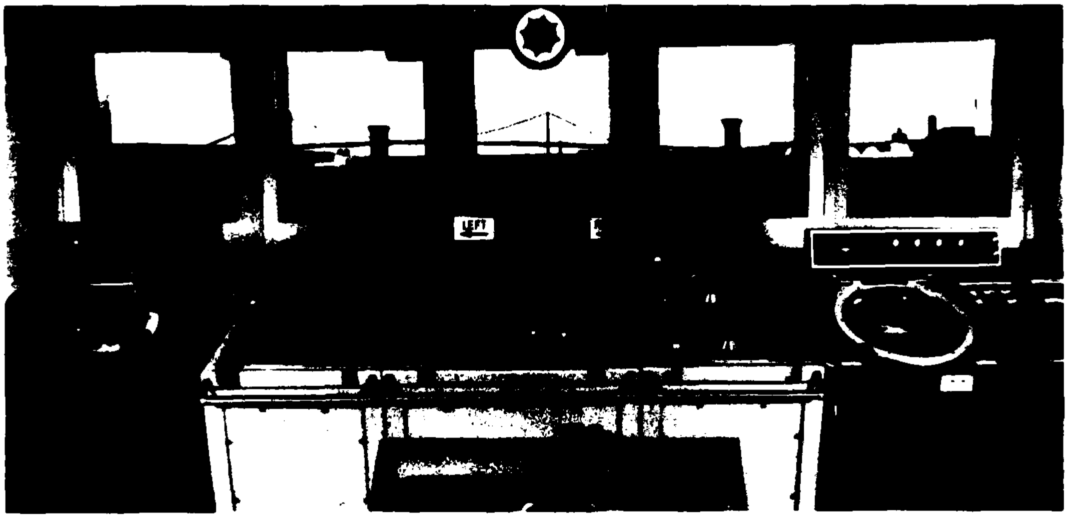

Figure A-3. Typical Simulated Visual Scene at CAORF

ownship appear. All elements in the scene appear to move in response to ownship's maneuvers. The sky is depicted without clouds and the water without waves.

For enhanced realism the scene is projected in full color. The perspective is set for the actual bridge height above waterline for the simulated ship. Shadowing can be varied according to the position of the sun at different times of day.

Environmental conditions also affect the scene. The lighting can be varied continuously from full sun to moonless night. At night, lights can be seen on traffic vessels, buoys, piers, and other points ashore. Visibility in the day or night can be reduced to simulate any degree of fog or haze.

A.5 RADAR SIGNAL GENERATION

The Radar Signal Generator produces real-time video signals for driving the two radar PPIs. The items displayed are synchronized with the visual scene and include navigation aids, ships, shorelines and other topographical features with appropriate target shadowing, clutter, range attenuation, and receiver noise. The radar gaming area, which covers an area of 150 by 200 miles, extends beyond the visual gaming area, which is 50 by 100 miles. Within the radar gaming area, as many as 40 moving traffic ships can be displayed. The radar signal generator also drives the collision avoidance system, which can be slaved to either of the master PPIs.

A.6 CONTROL STATION

The Control Station (Figure A-4) is the central location from which the simulator experiment is controlled and monitored. An experiment can be initiated anywhere within the visual gaming area with any ship traffic configuration. The Control Station enables the researchers to interface with the watchstanding crew on the bridge, to simulate malfunctions, and to control the operating mode of the simulator. The Control Station is also capable of controlling motions of traffic ships and tugs in the gaming area and simulating telephone, intercom, radio (VHF, SSB) and whistle contact with the CAORF bridge crew.

A.7 HUMAN FACTORS MONITORING STATION

The Human Factors Monitoring Station (Figure A-5) is designed to allow collection of data on crew behavior. Monitoring data is provided by five closed-circuit TV cameras and four microphones strategically located throughout the wheelhouse to record all activities, comments and commands.

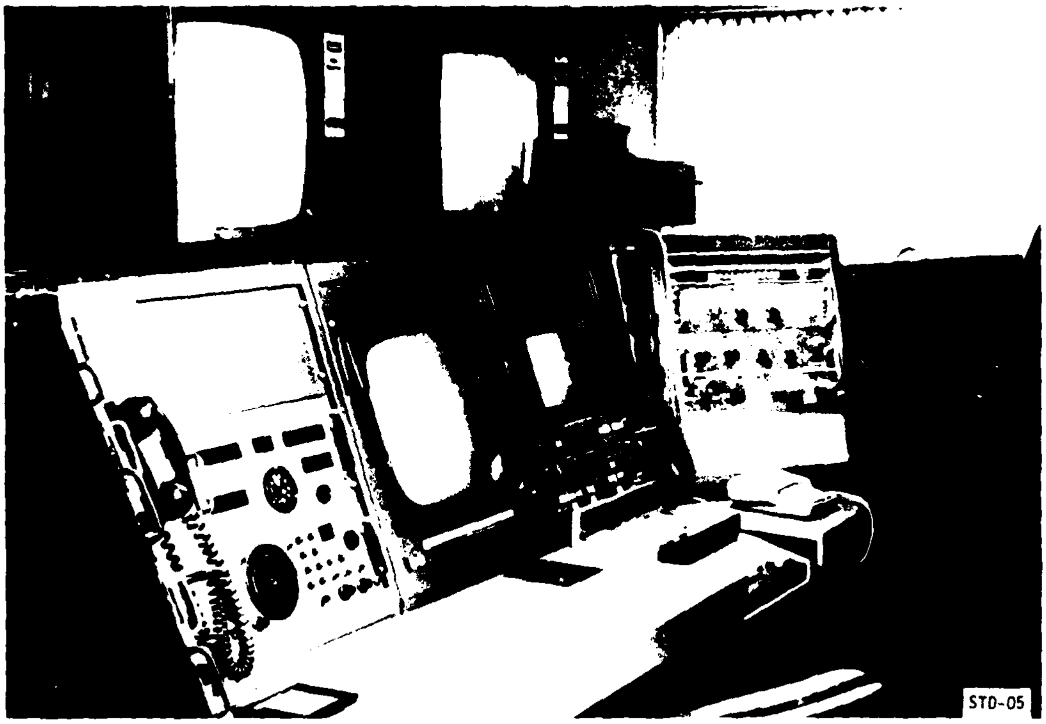

Figure A-4. Control Station

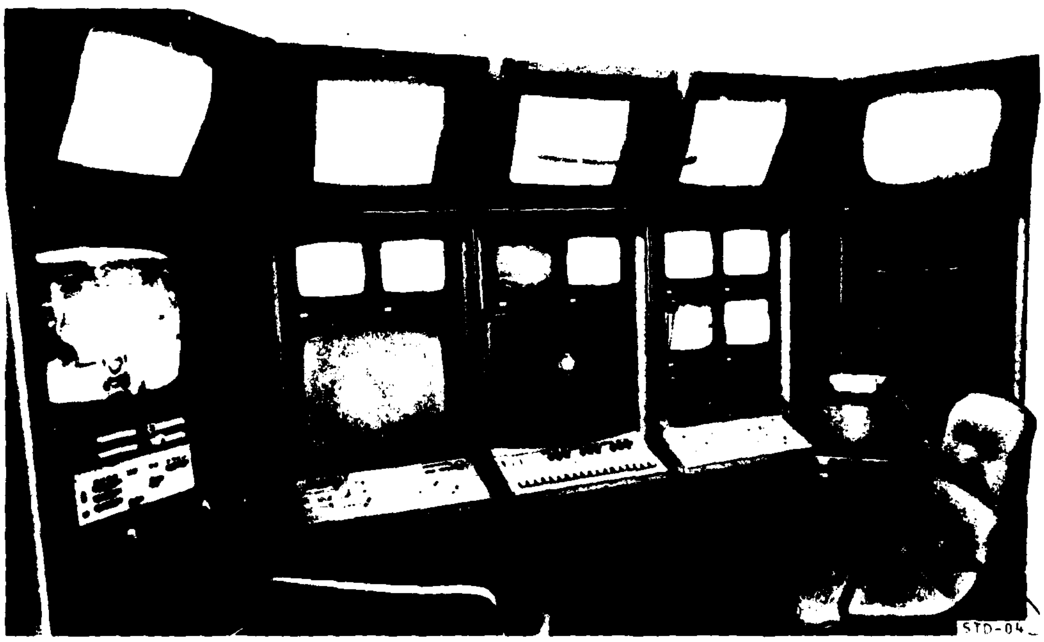

Figure A-5. Human Factors Monitoring Station

APPENDIX B

SHIP STABILITY AND THE SELECTION OF SHIP COEFFICIENTS

Theory predicts for the bare hull, when slender body theory is used, that the linear hydrodynamic coefficients can be expressed in terms of the aspect ratio, 2T/L, by

$$Y'_v = -\pi\ (T/L)^2$$

$$N'_v = -\pi/2\ (T/L)^2$$

$$Y'_r = +\pi/2\ (T/L)^2$$

$$N'_r = -\pi/4\ (T/L)^2$$

The primed coefficients are the conventional ones referred to the area L^2. L is ship length and T the draft. Also, in Dr. Eda and CAORF simulator notations

$Y'_v \equiv b_1 \equiv$ SCBP; $Y'_r \equiv b_2 =$ SCBP2; $N'_v = a_1 \equiv$ SCAP1, and $N'_r \equiv a_2 =$ SCAP2.

These simplified theoretical estimates, however, can give poor estimates of the coefficients (particularly N'_r) for the hull with appendages, particularly due to important propeller-rudder-hull interactions. For instance, in examining the Hydronautics' study(5) of a variety of configurations using PMM, it can be seen that the hull alone gave the major contribution to Y'_v and N'_v. The hull contributed about 40% and the rudder interaction about 60% to the N'_r coefficient, whereas the major contributor to Y'_r was due to the presence of the rudder. On the other hand, the coefficients did show variations with the normalized geometric parameters (L/B, T/B, and C_B) which were very similar to the bare hull case.

Norrbin (Sweden), Smitt (Denmark) and Glansdorp (Netherlands) have presented empirical relationships for ship models with rudder and propeller(s), based on a large number of model tests. These relationships, in slightly modified form were employed to select ships for this present experiment that would provide a sufficiently wide range of stability but yet be confined within practical and realistic limits. Norrbin used the so-called "BIS" system for normalizing coefficients which can be very simply modified to CAORF form (and those of Smitt and Glansdorp) by scaling by dimensionless mass, $m' = \frac{\rho\nabla}{\frac{1}{2}\rho L^3} = \frac{2\nabla}{L^3}$ (where ∇ is the displacement volume of the ship). For example, Norrbin gives $Y''_{uv} = -2.66\ (LT^2/\nabla) - 0.04$ from which $Y'_v = m'\ Y''_{uv} = -2.66\ (LT^2/\nabla)\ m' - 0.04\ m' = -5.32\ (T/L)^2 - 0.04\ m'$.

Norrbin used linear regression best fits to the data *in terms of* (LT^2/∇) *in the* case of all four coefficients. Consequently, each is defined in terms of a slope and a constant intercept. Smitt, on the other hand, simply fitted a best line through the origin with $(T/L)^2$ as his independent variable and in this way obtained expressions similar to the theoretical bare hull coefficients. This procedure appeared to give reasonable fits to the scattered data except in the case of N'_r, which had to be fitted by linear regression similar to Norrbin's procedure. The final coefficients derived in this manner were

$$Y'_v \sim -5.0\ (T/L)^2$$

$$N'_v \sim -1.94\ (T/L)^2$$

$$Y'_r \sim 1.02\ (T/L)^2$$

$$N'_r \sim -0.001 - 0.65\ (T/L)^2$$

Coefficients that have been used for CAORF ships as well as others extracted from the literature (Berkelom, Eda, Hydronautics, etc.) were plotted against $(T/L)^2$. They were found to lie within the scatter of data that can be adequately represented by the above relationships.

It was found convenient to adopt the LT^2/∇ notation where, of course, $(T/L)^2 = \frac{m}{2}(LT^2/\nabla)$.

Hence

$$Y'_v \sim -2.5\, m' (LT^2/\nabla)$$

$$N'_v \sim -0.97\, m' (LT^2/\nabla)$$

$$Y'_r \sim +0.51\, m' (LT^2/\nabla)$$

$$N'_r \sim -0.001 - 0.325\, m' (LT^2/\nabla)$$

The procedure that was used to generate the coefficients for the ships used in the experiment was to consider the existing 80K fully loaded tanker as the basic ship and to modify the coefficients systematically to obtain realistic unstable and stable ships, without specifying what exact changes in ship geometry would be required to accomplish these modifications (e.g., draft, length, beam, block coefficient, trim, shallow water effects, etc.). This basic 80K ship corresponds to an $LT^2/\nabla = 0.4$. The linear coefficients for this ship were then modified according to the LT^2/∇ ratios. The basic ship is slightly unstable. Stability calculations using the modified coefficients showed that smaller values of LT^2/∇ led to more unstable ships, while larger values increased the stability. A range of LT^2/∇ values within the limits of existing data (0.2, 0.3, 0.4, 0.8) was selected. The ships corresponding to these values have been designated A, B, C, E, respectively. Ship C, therefore, is the basic conventional 80,000 DWT tanker. The basic value of the linear coefficients Y'_v, N'_v, Y'_r of the 80,000 DWT tanker ($LT^2/\nabla = 0.4$) were then factored by the ratio of expressions evaluated at the given LT^2/∇ and at $LT^2/\nabla = 0.4$. The scaling factors for the coefficients were derived as indicated below and are shown in Table B-1 and graphically in Figure B-1.

For the N'_r coefficient, a linear relationship having the same slope as derived by Smitt was made to pass through the value at $LT^2/\nabla = 0.4$. In this way the intercept was slightly modified to -0.0011. The value of m' was maintained constant at $m' = .0138$, so

TABLE B-1. SHIP COEFFICIENTS

Ship Designation	$\frac{LT^2}{\nabla}$	Linear Coeffs. Y'_v, Y'_r, N'_v	Nonlinear and Rudder Coeffs.	N'_r
A	0.2	0.5	0.707	0.697
B	0.3	0.75	0.866	0.832
C	0.4	1.00	1.000	1.000
E	0.8	2.00	1.414	1.595

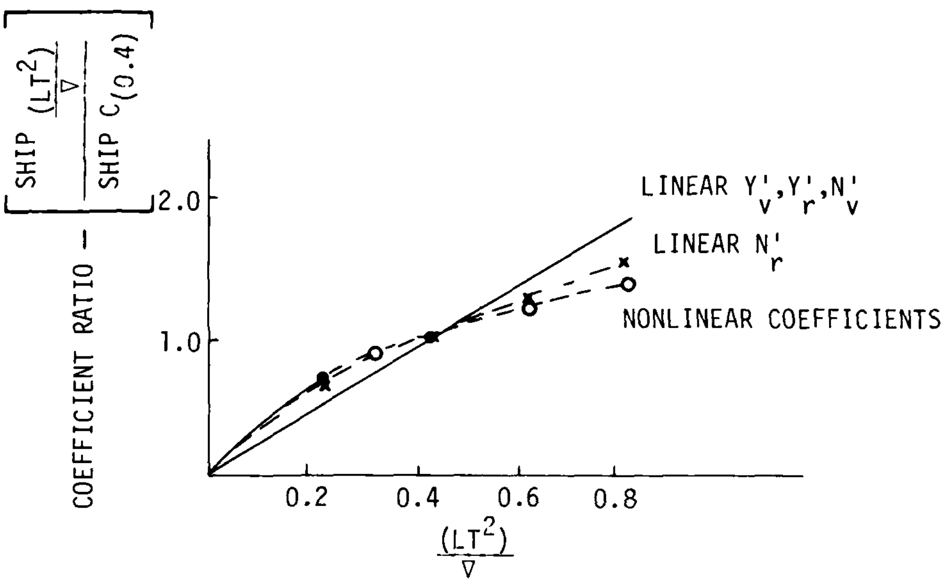

Figure B-1. Variation of Coefficient Ratio With Ship Parameter $\frac{LT^2}{\nabla}$

$Y'_v = -0.0345\,(LT^2/\nabla)$

$N'_v = -0.0134\,(LT^2/\nabla)$

$Y'_r = +0.00704(LT^2/\nabla)$

$N'_r = -0.0011 - 0.004485(LT^2/\nabla)$

The non-linear hull coefficients and the rudder force and moment coefficients were varied and approximated by assuming that they were essentially draft dependent, i.e., they varied as $\sqrt{\frac{LT^2}{\nabla}}$.

STABILITY CALCULATIONS

The requirement for stability is that the damping lever arm (ℓ'_r) be greater than the static stability lever arm (ℓ'_v) i.e., $\ell'_d = \ell'_r - \ell'_v > 0$.

$$\text{Now, } \ell'_r - \ell'_r = \frac{N'_r}{(Y'_r - m')} - \frac{N'_v}{Y'_v}$$

$$= \frac{N'_r Y'_v - N'_v (Y'_r - m')}{Y'_v (Y'_r - m')} = \frac{C}{Y'_v (Y'_r - m')}$$

S nce Y'_v and $(Y'_r - m')$ are both negative the stability requirement is that $C > 0$. This relationship involves only the linear hull coefficients and the ship's mass.

The eigenvalues for steady state straight line motion with rudder fixed amidship are

$$\sigma_{1,2} = -\frac{B}{2A}\left|1 \mp \sqrt{1 - \frac{4AC}{B^2}}\right|$$

where $A = (m' - b_{12})(I'_z - a_{11})$

$B = -b_1 (I'_z - a_{11}) - a_2 (m' - b_{12})$

$C = b_1 a_2 - a_1 (b_2 - m')$

again involving the linear coefficients and the effective mass and moment of inertia.

Since A and B^2 are always positive the behavior of the eigenvalues depends upon the sign of C. If C is negative, there will exist a positive eigenvalue which represents an unstable condition with an exponentially growing response to small initial disturbances.

The eigenvalues calculated for the four values of the parameter LT^2/∇, are shown in Figure B-2. These refer to the ship without any external wind disturbances. However, it is known from a previous CAORF study, Ship Characteristics Experiment[6] that wind strength and direction can play a large part in modifying the ship's stability characteristics. In the experiment reported herein, a wind is present, and consequently an off-line study was made into the influence of a thirty knot beam wind on the stability of the four ships transiting at six knots. The modified eigenvalues are also shown in Figure B-2. It can be seen that the stable ship becomes much less stable, whereas the unstable one becomes more stable. The standard 80,000 DWT ship is not effected to any great extent. The influence of wind direction on eigenvalues showed that, whereas the unstable ship remained unstable independent of wind direction, the stable one exhibits a positive eigenvalue with wind on the port or starboard quarters.

The degree of instability is commonly represented by the amount of hysteresis in the steering characteristics curve (r, δ). The slope of this curve at the origin indicates the stability: negative slope is stable, positive slope is unstable, infinite slope is marginally stable. The slope depends not only upon the linear hull coefficients and the corresponding value of 1/C, but also on the actual rudder coefficients (Y'_δ, N'_δ). The smaller Y'_δ becomes, the less effective is the rudder and the less stable or unstable the ship be-

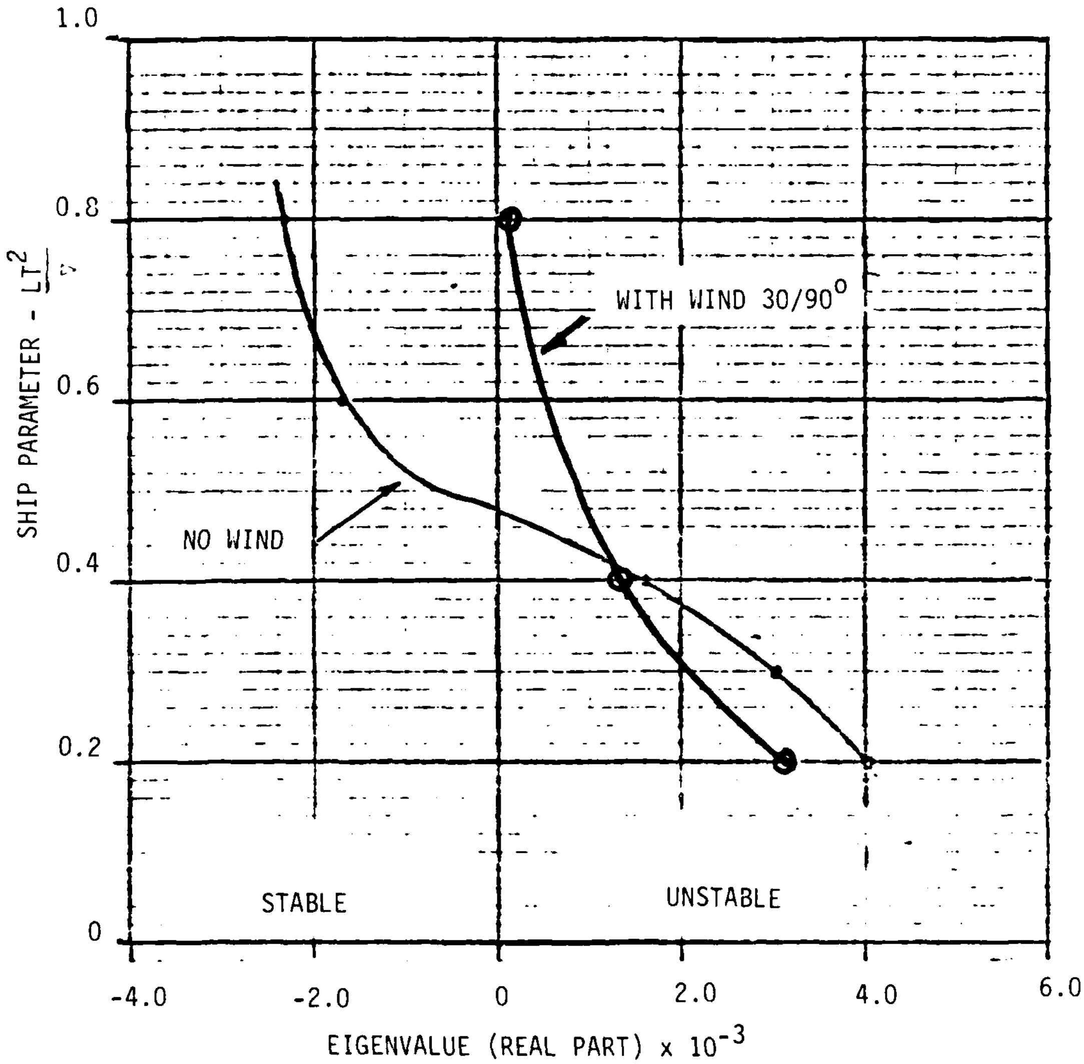

Figure B-2. Longitudinal Stability Characteristics for the 80K Tanker (Deep Water) with Variations in $\frac{LT^2}{\nabla}$

comes. The hysteresis effect can be magnified by increasing C and decreasing Y'_{δ}.

Based on this procedure of scaling hull coefficients as well as the rudder and nonlinear coefficients in accordance with Table B-1, the steering characteristics (Rudder Angle vs. Heading Rate) of the four ships were derived and are shown in the following figure, Figure B-3.

MANEUVERING CHARACTERISTICS OF THE SELECTED SHIPS

Turning Circles, 10°/10° Zig-Zags Crash Stops

In Figures B-4 to B-7 turning circles determined in off-line studies are shown for all four ships, and in Table B-2 comparisons are made with pre-simulation runs made on-line for validation of Ships A, C and E. 10°/10° Zig-Zags were performed both on-line and off-line for the standard ship (C) and the two extremes (A and E), and again in Table B-3 comparisons are shown. The advance and transfer and corresponding times for crash stops starting at speeds corresponding to throttle positions full ahead, half ahead and slow ahead (Table B-4) were determined for the standard and extreme ships. Results are tabulated in Table B-5. The turning circle and stopping data were inserted in wheelhouse maneuvering information charts that were supplied to the test subjects for each individual ship.

TABLE B-2. TURNING MANEUVER CHARACTERISTICS

$\frac{LT^2}{\nabla}$	0.2 (Ship A)		0.4 (Ship C)		0.8 (Ship E)	
Speed (knots)	15	(6)	15	(6)	15	(6)
RPM	92	(36.92)	102	(40.90)	115	(45.81)
Advance (feet)	3,051	(2,900)	2,543	(2,330)	1,855	(2,030)
Max. Transfer (feet)	2,829	(2,850)	2,462	(2,480)	2,447	(2,420)
T. C. Diameter (feet)	1,695	(1,850)	1,512	(1,580)	1,595	(1,500)

NOTE: Values in brackets correspond to the results of off-line studies using the ship dynamic section of the Optimal Control Program. The differences in results are due mainly to the time required to build up rudder angle, which is assumed instantaneous in the off-line calculations but requires approximately 15 seconds on the simulator. At 6 knots (10 FPS) this accounts for a discrepancy of the order of 100 feet. Also, data from the simulator have been interpolated from 10 second data logs (with possible additional errors of 100 ft.)

TABLE B-3. 10°/10° ZIG-ZAG AT 6 KNOTS

$\frac{LT^2}{\nabla}$	0.2 (Ship A)		0.4 (Ship C)		0.8 (Ship E)	
Overshoot Yaw Angle (deg.)	13.64	(10)	10.73	(7.0)	6.61	(3.3)
Reach (min.)	10.50	(9.5)	8.00	(6.7)	5.33	(4.9)
Period (min.)	25.50	(23.6)	14.16	(13.0)	9.16	(8.4)
1st Execute (min.)	0	0	0	0	0	0
2nd Execute (min.)	2.16	(2.1)	2.5	(2.0)	1.67	(2.0)
3rd Execute (min.)	11.50	(10.4)	8.9	(7.5)	6.33	(6.0)
4th Execute (min.)	28.15	(25.8)	16.7	(15.0)	11.0	(10.4)
1st Overshoot (ft.)	+1,455	(+1,000)	+900	-	+510	(+150)
2nd Overshoot (ft.)	-2,624	(-2,500)	-361	-	+18	-

NOTE: (1) The Zig-Zag maneuvers were performed both on the simulator, where the control was performed by the control operator, and with the off-line program, where the controls were automatically preprogrammed. The values in brackets in the table correspond to the off-line calculations. Large discrepancies between the programmed off-line rudder reversals and the manual changes by control operator personnel can occur and give relatively large values. Also, as before, the off-line runs do not account for the finite time required to build up Rudder Angle.

(2) The following diagram defines the terms used in the table.

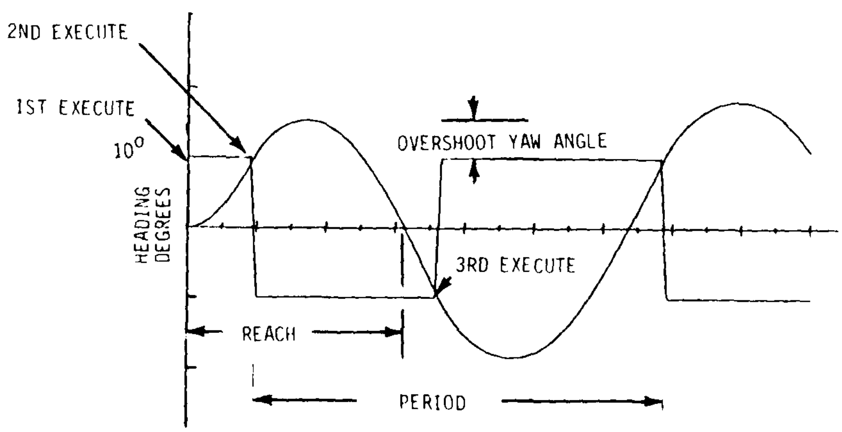

TABLE B-4. EQUILIBRIUM SHIP SPEED (KNOTS) VS. ENGINE SPEED (RPM)

$\frac{LT^2}{V}$	0.2 (Ship A)	0.4 (Ship C)	0.8 (Ship E)
Engine Full Ahead (60 RPM)	9.8	8.8	7.9
Engine Half Ahead (40 RPM)	6.5	5.9	5.2
Engine Slow Ahead (20 RPM)	3.3	2.9	2.6

TABLE B-5. STOPPING DISTANCES

$\frac{LT^2}{V}$	0.2 (Ship A)	0.4 (Ship C)	0.8 (Ship E)
ENGINE FULL AHEAD			
Stopping Dist. (miles)	0.67	0.95	0.55
Stopping Time (min.)	8.5	13.8	8.7
Transfer (miles)	0.13	0.08	0.02
ENGINE HALF AHEAD			
Stopping Dist. (miles)	0.41	0.51	0.28
Stopping Time (min.)	7.3	10.5	6.2
Transfer (miles)	0.02	0.02	0
ENGINE SLOW AHEAD			
Stopping Dist. (miles)	0.13	0.11	-
Stopping Time (min.)	4.2	4.0	-
Transfer (miles)	0	0	-

NOTE: These runs were based on the time to reach a fore-aft speed of 0.2 knots through water. The stopping distance, S, in nautical miles, can be represented very closely by the expression

$S = \frac{4}{300} V^2$ where V is the initial ship equilibrium speed, in knots.

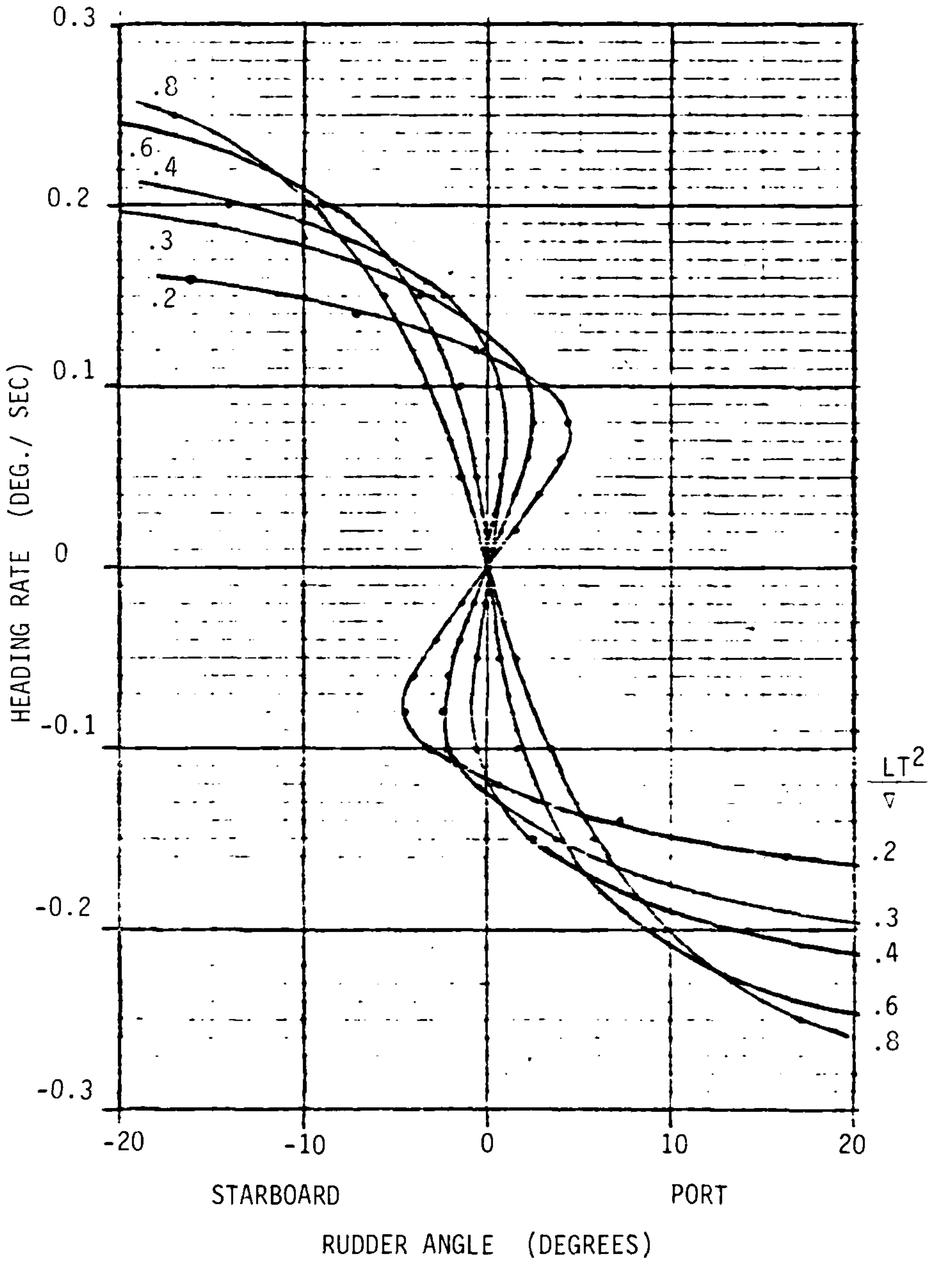

Figure B-3. Steady-State Heading Rate vs. Rudder Deflection for Variations in $\frac{LT^2}{\nabla}$

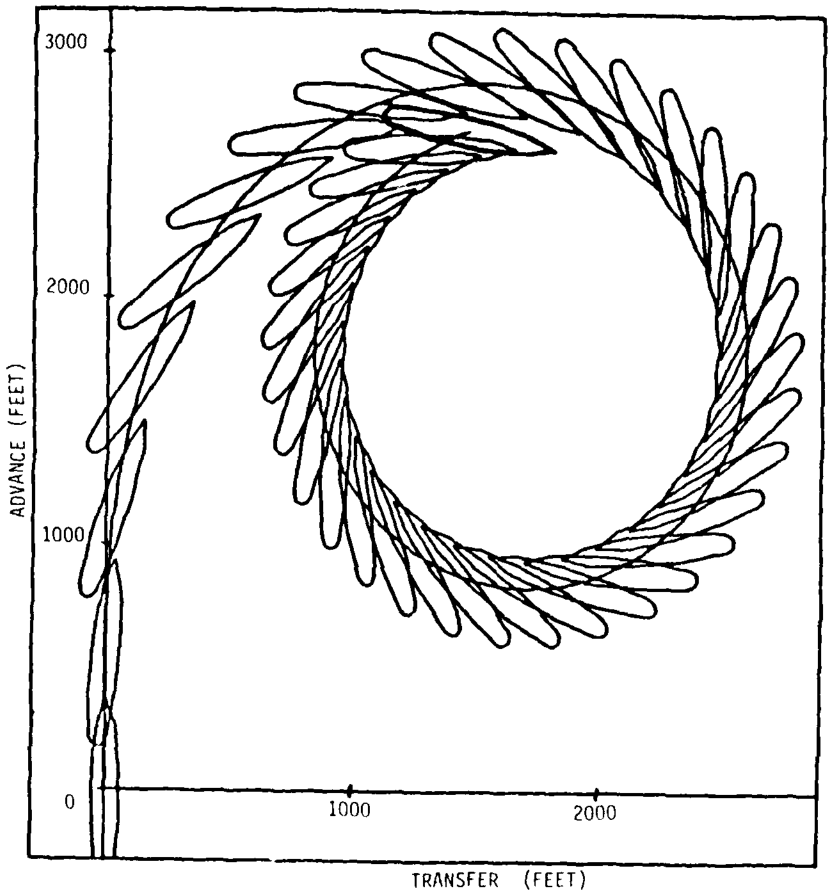

Figure B-4. Turning Circle - $\frac{LT^2}{\nabla}$ = 0.2 (Ship A)

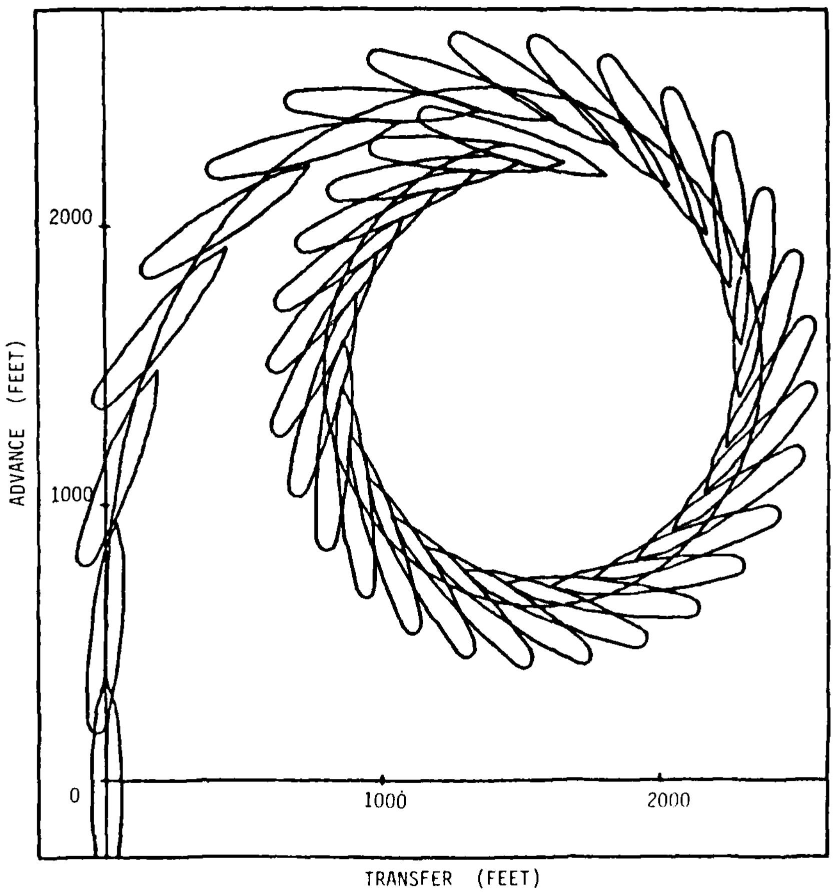

Figure B-5. Turning Circle - $\frac{LT^2}{\nabla}$ *= 0.3 (Ship B)*

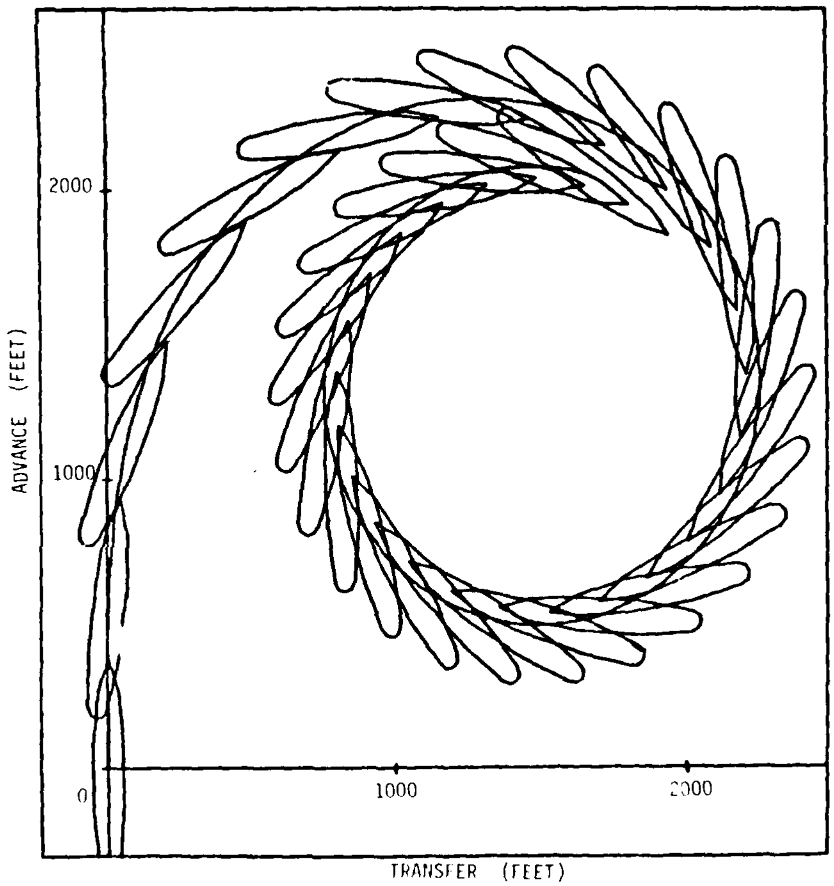

Figure B-6. Turning Circle - $\frac{LT^2}{\nabla} = 0.4$ *(Ship C)*

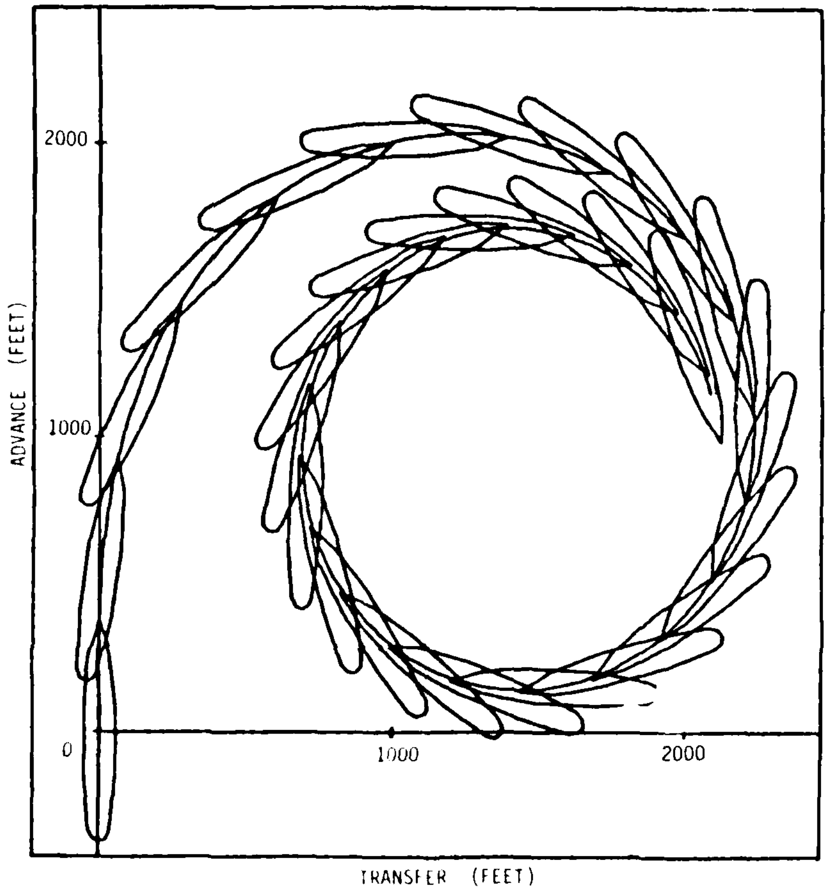

Figure B-7. Turning Circle - $\frac{LT^2}{\nabla} = 0.8$ (Ship E)

APPENDIX C
STATISTICAL ANALYSIS

The experiment design was structured around 2 principle independent variables.

A - Ship Inherent Maneuverability (4 levels)
- Ship A Unstable
- Ship B Moderately Unstable
- Ship C Moderately Stable
- Ship E Stable

B - Channel Legs (5 Levels)
- Leg 2
- Leg 3
- Leg 4
- 90^o Turn
- Leg 6

These variables were combined in a Two-Factor Within Subject Design with each subject experiencing each of the four ships in each channel segment. A total of 64 runs comprised the experiment (sixteen subjects @ four runs) with the order of testing of ships randomized throughout.

Two complete sets of ANOVAS were performed making use of the data obtained from the experimental runs. The primary set of analyses were based on the variables of ship and channel legs. A secondary set was performed on the same data using run-order and channel legs as the variables under comparison. The "A" variable (RUN NUMBER) was also at 4 levels for this second set of analyses.

DATA ANALYSIS

Throughout this Appendix frequent reference is made to the "probability" or "level of significance" associated with specific results of statistical analyses. The reported probability value (p) represents the likelihood that results as large or larger than those obtained in the experiment data analysis could be due to random or chance factors outside the scope of the investigation. In other words, if one were comparing two sample statistics, e.g., means, and reported that the means differed significantly from one another at the $p \leq 0.05$ level of significance, there is a probability of no greater than 0.05 that the observed difference was due to chance variation. Therefore, there is a 0.95 probability that the difference observed in the sample reflects a difference attributable to some systematic influence, i.e., a factor systematically manipulated in the experiment. Such differences are referred to as "statistically significant."

PERFORMANCE MEASURES

Ten performance measures were assessed via the Analysis of Variance in this experiment.

1 - Ship Velocity Over the Ground (VOS)
2 - Swept Path
3 - % of Time VOS Over 7 Knots
4 - Average Off-Track Deviation ($\bar{X}$)
5 - Boundary Penetrations (Transformed)
6 - Boundary Penetrations (Non-transformed)
7 - Root Mean Square of Off-Track Deviation (X_{RMS})
8 - Total Rudder Command Rate
9 - Total Command Rate
10 - Consistency (Standard

Deviation of Off-Track Deviation)

In all cases these measures were computed across five sections of the test channel. One of the performance measures, Boundary Penetrations, was transformed using a square root transformation ($X^+ = \sqrt{X} + \sqrt{X+1}$) prior to application of the analysis of variance. This transformation was chosen based on observed relationships between treatment condition means and variances within these measures; tabular presentation of both transformed and non-transformed data is duly noted in the tables which follow.

Eleven additional measures were analyzed for ship-order effects and run-order effects by using a second ANOVA model in accordance with the source table C-19. These measures were based on happenings which occurred once per run, either "totals" for a measure previously analyzed across the leg variable, or an item which occurred at only one point in the channel. These measures were:

11 - VOS (Total)
12 - Swept Path (Total)
13 - VOS at End of Run
14 - % of Time VOS Over 7 Knots (Total)
15 - $\bar{X}$ (Total)
16 - Boundary Penetrations - Transformed (Total)
17 - Boundary Penetrations - Non-Transformed (Total)
18 - X_{RMS} (Total)
19 - Transit Time for Legs 2 through 90° Turn
20 - Distance Off Buoy #1
21 - Consistency (Total)

Relationships among means for ship type, channel legs and run-order as well as comparisons among these means are presented in Table C-1 through C-6. Interactions of ship and leg as well as run-order and leg are also contained in the tables within this Appendix.

CONFIDENCE INTERVALS

In research one is frequently interestd in drawing inferences about population parameters when only sample statistics are available. A technique useful for the purpose is the generation of confidence intervals.

When a sample statistic is computed, for example a sample mean, a confidence interval can be calculated around this mean. The confidence interval is a prediction of the limits within which the actual population parameter mean (μ) is likely to fall. Furthermore this range is stated probabilistically, reflecting the degree of certainty in the prediction, for example, 90% or 95% certainty or confidence.

Ninety-five percent confidence intervals were computed for both the mean and standard deviation of Root Mean Square of Off-Track Deviation and Consistency (Table C-18). The procedures that were used are described in Snedecor and Cochran, 1967.

TABLE C-1. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (MAIN EFFECTS)

Parameter	A	B	C	E	P <
VOS - Kts.	6.754	6.059	6.312	5.977	0.05
Swept Path (SP) - Ft.	228.2	206.4	194.9	174.1	0.001
Percentage of Time Over 7 Knots - %	0.366	0.255	0.297	0.202	0.01
Average Off-Track Deviation (OTD) - Ft.	-65.79	-19.19	-10.43	10.34	0.001
BP (Transformed) - #/Sub	1.76	1.16	1.11	1.05	0.001
BP (Non-Transformed) #/Sub	0.575	0.113	0.088	0.038	0.001
RMS OTD - Ft.	152.9	97.1	92.6	85.0	0.001
Total Rudder Commands #/Min	1.66	1.75	1.79	1.58	ns
Total Commands - #/Min	1.94	1.96	1.99	1.75	ns
SD of OTD - Ft.	102.2	64.4	57.0	47.3	0.001
VOS (Total) - Kts.	6.214	5.420	5.645	5.464	0.05
Swept Path (Total) - Ft.	216.8	193.5	182.2	166.2	0.001
VOS End of Run - Kts.	3.25	2.58	2.63	2.50	ns
Percentage of Time Over 7 Kts (Total) - %	0.483	0.330	0.385	0.303	0.01
Average OTD (Total) - Ft.	-55.42	-15.21	-13.14	0.43	0.001
BP Transformed (Total) #/Sub	3.14	1.58	1.44	1.18	0.001
BP Non-Transformed (Total) - #/Sub	2.13	0.50	0.38	0.13	0.001
RMS OTD (Total) - Ft.	158.3	98.1	90.1	82.9	0.001
Time (Leg 2-5) - Min	34.7	38.1	36.5	37.7	ns
OTD at Buoys 1-2 - Ft.	461.5	407.5	419.8	339.7	ns
SD of OTD (Total) - Ft.	140.6	92.8	82.7	76.2	0.001

NOTE: VOS = Ship Speed Over Ground
BP = Boundary Penetrations
RMS = Root Mean Square
SD = Standard Deviation
ns = Non-Significant
Transformation: $X' = \sqrt{X} + \sqrt{X+1}$

TABLE C-2. COMPARISON AMONG MEANS FOR SHIP TYPE (MAIN EFFECTS)

Parameter	A-B	A-C	A-E	B-C	B-E	C-E
VOS	*	ns	*	ns	ns	ns
Swept Path	**	**	**	**	**	**
Percentage of Time Over 7 Knots	*	ns	**	ns	ns	ns
Average Off-Track Deviation	**	**	**	ns	*	*
BP (Transformed)	**	**	**	ns	ns	ns
BP (Non-Transformed)	**	**	**	ns	ns	ns
RMS OTD	**	**	**	ns	ns	ns
Total Rudder Commands	--	--	--	--	--	--
Total Commands	--	--	--	--	--	--
SD of OTD	**	**	**	ns	ns	ns
VOS (Total)	*	*	*	ns	ns	ns
Swept Path (Total)	**	**	**	**	**	**
VOS End of Run	--	--	--	--	--	--
Percentage of Time Over 7 Kts (Total)	**	*	**	ns	ns	ns
Average OTD (Total)	**	**	**	ns	ns	ns
BP Transformed (Total)	**	**	**	ns	ns	ns
BP Non-Transformed (Total)	**	**	**	ns	ns	ns
RMS OTD (Total)	**	**	**	ns	ns	ns
Time (Leg 2-5)	--	--	--	--	--	--
OTD at Buoys 1-2	--	--	--	--	--	--
SD of OTD (Total)	**	**	**	ns	ns	ns

** = $p < 0.01$
* = $p < 0.05$
ns = non-significant

TABLE C-3. RELATIONSHIP AMONG MEANS FOR CHANNEL LEG (MAIN EFFECTS)

Parameters	1	2	3	4	5	P <
VOS - Kts.	8.62	7.36	6.29	5.22	3.89	0.001
Swept Path - Ft.	209.9	168.4	205.0	255.2	166.0	0.001
Percentage of Time Over 7 Kts - %	0.692	0.503	0.166	0.026	0.012	0.001
Average Off-Track Deviation - Ft.	-24.3	24.1	-62.1	-26.9	-17.0	0.001
BP (Transformed) #/Sub	1.13	1.02	1.36	1.33	1.51	0.001
BP (Non-Transformed) #/Sub	0.09	0.02	0.27	0.23	0.41	0.001
RMS OTD - Ft.	125.1	73.5	124.5	137.0	74.4	0.001
Total Rudder Commands - #/Min	2.09	1.76	1.60	1.85	1.19	0.001
Total Commands - #/Min	2.34	1.89	1.81	2.08	1.43	0.001
SD of OTD - Ft.	77.5	51.2	89.0	57.5	63.4	0.001

TABLE C-4. COMPARISON AMONG MEANS FOR CHANNEL LEG (MAIN EFFECTS)

Parameter	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
VOS	**	**	**	**	**	**	**	**	**	**
Swept Path	**	ns	**	**	**	**	ns	**	**	**
Percentage of Time Over 7 Knots	**	**	**	**	**	**	**	ns	ns	ns
Average Off-Track Deviation	*	ns	ns	ns	**	*	*	ns	ns	ns
BP (Transformed)	ns	**	*	**	**	**	**	ns	*	*
BP (Non-Transformed)	ns	*	ns	**	**	**	**	ns	*	**
RMS OTD	**	ns	ns	**	**	**	ns	ns	**	**
Total Rudder Commands	ns	**	ns	**	ns	ns	**	ns	**	**
Total Commands	**	**	*	**	ns	ns	**	ns	*	**
SD of OTD	**	ns	**	ns	**	ns	ns	**	**	ns

TABLE C-5. RELATIONSHIP AMONG MEANS FOR RUN ORDER (MAIN EFFECTS)

Parameter	1st	2nd	3rd	4th	P <
VOS - Kts.	5.74	6.30	6.47	6.59	0.01
Swept Path - Ft.	205.1	203.6	197.8	197.2	ns
Percentage of Time Over 7 Kts. - %	0.240	0.295	0.279	0.307	ns
Average Off-Track Deviation - Ft.	-29.75	-20.91	-12.87	-21.53	ns
BP (Transformed) #/Sub	1.336	1.239	1.275	1.240	ns
BP (Non-Transformed) #/Sub	0.238	0.175	0.213	0.188	ns
RMS OTD - Ft.	112.7	108.9	103.4	102.7	ns
Total Rudder Commands #/Min	1.65	1.76	1.71	1.67	ns
Total Commands #/Min	1.87	1.98	1.90	1.88	ns
SD of OTD - Ft.	75.3	68.3	66.7	60.5	ns
VOS (Total) - Kts.	5.14	5.66	6.00	5.94	0.01
Swept Path (Total) - Ft.	193.8	190.3	187.4	187.1	ns
VOS End of Run - Kts.	2.59	2.70	3.03	2.65	ns
Percentage of Time Over 7 Kts (Total) - %	0.324	0.374	0.400	0.403	ns
Average OTD (Total) - Ft.	-19.77	-20.56	-17.97	-25.06	ns
BP Transformed (Total) #/Sub	2.061	1.750	1.823	1.698	ns
BP Non-Transformed (Total) - #/Sub	0.938	0.688	0.813	0.688	ns
RMS OTD (Total) - Ft.	113.3	108.1	104.3	103.6	ns
Time (Leg 2-5) - Min.	39.5	36.4	35.9	35.2	0.01
OTD at Buoys 1-2 - Ft.	319.9	395.7	466.4	446.6	0.01
SD of OTD (Total) - Ft.	104.8	99.8	97.4	90.3	ns

TABLE C-6. COMPARISON AMONG MEANS FOR RUN ORDER (MAIN EFFECT)

Parameter	1-2	1-3	1-4	2-3	2-4	3-4
VOS	ns	*	**	ns	ns	ns
Swept Path	--	--	--	--	--	--
Percentage of Time Over 7 Knots	--	--	--	--	--	--
Average Off-Track Deviation	--	--	--	--	--	--
BP (Transformed)	--	--	--	--	--	--
BP (Non-Transformed)	--	--	--	--	--	--
RMS OTD	--	--	--	--	--	--
Total Rudder Commands	--	--	--	--	--	--
Total Commands	--	--	--	--	--	--
SD of OTD	--	--	--	--	--	--
VOS (Total)	ns	*	*	ns	ns	ns
Swept Path (Total)	--	--	--	--	--	--
VOS End of Run	--	--	--	--	--	--
Percentage of Time Over 7 Kts (Total)	--	--	--	--	--	--
Average OTD (Total)	--	--	--	--	--	--
BP Transformed (Total)	--	--	--	--	--	--
BP Non-Transformed (Total)	--	--	--	--	--	--
RMS OTD (Total)	--	--	--	--	--	--
Time (Leg 2-5)	*	*	**	ns	ns	ns
OTD at Buoys 1-2	ns	**	ns	ns	ns	ns
SD of OTD (Total)	--	--	--	--	--	--

TABLE C-7. RELATIONSHIP AMONG MEANS FOR SHIP TYPE BY CHANNEL LEG VOS (KNOTS)

	Channel Leg					Interaction	Comparisons									
	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
Ship Type																
A	9.318	7.769	6.892	5.356	4.435	0.05	**	**	**	**	**	**	**	**	**	**
B	8.509	7.239	6.029	4.922	3.595		**	**	**	**	**	**	**	**	**	**
C	8.894	7.448	6.181	5.201	3.836		**	**	**	**	**	**	**	**	**	**
E	7.771	6.965	6.067	5.408	3.675		**	**	**	**	**	**	**	ns	**	**
Comparisons																
A-B	**	ns	*	ns	*											
A-C	ns	ns	*	ns	*											
A-E	**	*	**	ns	*											
B-C	ns	ns	ns	ns	ns											
B-E	*	ns	ns	ns	ns											
C-E	**	ns	ns	ns	ns											

TABLE C-8. RELATIONSHIP AMONG MEANS FOR SHIP TYPE BY CHANNEL LEG SWEPT PATH (FEET)

	Channel Leg					Interaction	Comparisons									
Ship Type	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
A	218.7	179.5	233.0	310.5	199.2	0.001	**	ns	**	*	**	**	*	**	**	**
B	210.7	171.0	216.1	270.3	164.1		**	ns	**	**	**	**	ns	**	**	**
C	207.1	163.8	197.7	252.3	153.5		**	ns	**	**	**	**	ns	**	**	**
E	203.3	159.4	173.1	187.5	147.1		**	**	*	**	ns	**	ns	ns	**	**

Comparisons	1	2	3	4	5
A-B	ns	ns	**	**	**
A-C	ns	*	**	**	**
A-E	ns	**	**	**	**
B-C	ns	ns	**	**	ns
B-E	ns	ns	**	**	*
C-E	ns	ns	**	**	ns

TABLE C-9. RELATIONSHIP AMONG MEANS FOR SHIP TYPE BY CHANNEL LEG PERCENTAGE OF TIME OVER 7 KNOTS (%)

	Channel Leg					Interaction	Comparisons									
Ship Type	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
A	0.725	0.580	0.395	0.083	0.048	0.01	*	**	**	**	*	**	**	**	**	ns
B	0.766	0.427	0.082	0.000	0.000		**	**	**	**	**	**	**	ns	ns	ns
C	0.731	0.607	0.125	0.021	0.002		ns	**	**	**	**	**	**	ns	ns	ns
E	0.547	0.399	0.063	0.000	0.000		*	**	**	**	**	**	**	ns	ns	ns
Comparisons																
A-B	ns	ns	**	ns	ns											
A-C	ns	ns	**	ns	ns											
A-E	*	*	**	ns	ns											
B-C	ns	*	ns	ns	ns											
B-E	**	ns	ns	ns	ns											
C-E	*	*	ns	ns	ns											

TABLE C-10. RELATIONSHIP AMONG MEANS FOR SHIP TYPE BY CHANNEL LEG AVERAGE OFF-TRACK DEVIATION (FEET)

	Channel Leg					Interaction	Comparisons									
	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
Ship Type																
A	-28.7	41.0	-108.9	-180.8	-51.5	0.001	**	**	**	ns	**	**	**	**	*	**
B	-18.6	24.0	-83.4	-16.1	-1.9		ns	*	ns	ns	**	ns	ns	*	**	ns
C	-5.4	14.8	-44.7	-8.3	-8.4		ns	ns	ns	ns	*	ns	ns	ns	ns	ns
E	-44.6	16.6	-11.5	97.4	-6.2		*	ns	**	ns	ns	**	ns	**	ns	**
Comparisons																
A-B	ns	ns	ns	**	ns											
A-C	ns	ns	ns	**	ns											
A-E	ns	ns	**	**	ns											
B-C	ns	ns	ns	ns	ns											
B-E	ns	ns	**	**	ns											
C-E	ns	ns	ns	**	ns											

TABLE C-11. RELATIONSHIP AMONG MEANS FOR SHIP TYPE BY CHANNEL LEG BOUNDARY PENETRATIONS - NON-TRANSFORMED (#/SUBJECT)

	Channel Leg					Interaction	Comparisons									
	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
Ship Type																
A	0.063	0.063	0.813	0.750	1.188	0.001	ns	**	**	**	**	**	**	ns	**	**
B	0.125	0.000	0.188	0.063	0.188		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C	0.125	0.000	0.063	0.063	0.188		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
E	0.063	0.000	0.000	0.063	0.063		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Comparisons																
A-B	ns	ns	**	**	**											
A-C	ns	ns	**	**	**											
A-E	ns	ns	**	**	**											
B-C	ns	ns	ns	ns	ns											
B-E	ns	ns	ns	ns	ns											
C-E	ns	ns	ns	ns	ns											

TABLE C-12. RELATIONSHIP AMONG MEANS FOR SHIP TYPE BY CHANNEL LEG BOUNDARY PENETRATIONS - TRANSFORMED (#/SUBJECT)

	Channel Leg					Interaction	Comparisons									
	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
Ship Type																
A	1.09	1.09	2.11	2.06	2.47	0.001	ns	**	**	**	**	**	**	ns	*	*
B	1.18	1.00	1.27	1.09	1.27		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
C	1.18	1.00	1.09	1.09	1.22		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
E	1.09	1.00	1.00	1.09	1.09		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Comparisons																
A-B	ns	ns	**	**	**											
A-C	ns	ns	**	**	**											
A-E	ns	ns	**	**	**											
B-C	ns	ns	ns	ns	ns											
B-E	ns	ns	ns	ns	ns											
C-E	ns	ns	ns	ns	ns											

TABLE C-13. RELATIONSHIP AMONG MEANS FOR SHIP TYPE BY CHANNEL LEG RMS - OFF-TRACK DEVIATION (FEET)

	Channel Leg					Interaction	Comparisons									
	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
Ship Type																
A	127.4	94.9	187.9	211.2	142.9	0.001	ns	**	**	ns	**	**	*	ns	*	**
B	118.4	72.2	128.7	98.6	67.8		*	ns	ns	*	**	ns	ns	ns	**	ns
C	122.8	61.8	107.2	119.4	51.8		**	ns	ns	**	*	**	ns	ns	**	**
E	131.9	65.0	74.0	118.8	35.2		**	**	ns	**	ns	**	ns	*	ns	**
Comparisons																
A-B	ns	ns	**	**	**											
A-C	ns	ns	**	**	**											
A-E	ns	ns	**	**	**											
B-C	ns	ns	ns	ns	ns											
B-E	ns	ns	**	ns	ns											
C-E	ns	ns	ns	ns	ns											

TABLE C-14. RELATIONSHIP AMONG MEANS FOR SHIP TYPE BY CHANNEL LEG
TOTAL RUDDER COMMAND (#/MINUTES)

	Channel Leg					Interaction	Comparisons									
	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
Ship Type																
A	2.01	1.69	1.76	1.56	1.30	0.05	ns	ns	*	**	ns	ns	ns	ns	*	ns
B	2.09	1.80	1.54	2.14	1.20		ns	**	ns	**	ns	ns	**	**	ns	**
C	2.36	1.89	1.58	1.87	1.26		**	**	**	**	ns	ns	**	ns	ns	**
E	1.91	1.66	1.51	1.82	1.01		ns	**	ns	**	ns	ns	**	ns	*	**
Comparisons																
A-B	ns	ns	ns	**	ns											
A-C	ns	ns	ns	ns	ns											
A-E	ns	ns	ns	ns	ns											
B-C	ns	ns	ns	**	ns											
B-E	ns	ns	ns	ns	ns											
C-E	*	ns	ns	ns	ns											

TABLE C-15. RELATIONSHIP AMONG MEANS FOR SHIP TYPE BY CHANNEL LEG STANDARD DEVIATION OF OFF-TRACK DEVIATION (FEET)

	Channel Leg					Interaction	Comparisons									
	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
Ship Type																
A	72.4	75.4	136.1	104.9	122.0	0.001	ns	**	**	**	**	**	**	**	ns	ns
B	76.1	54.6	86.2	44.0	61.2		ns	ns	**	ns	**	ns	ns	**	*	ns
C	75.8	39.7	77.4	48.2	44.1		**	ns	**	**	**	ns	ns	**	**	ns
E	85.7	35.0	56.4	32.9	26.3		**	**	**	**	*	**	ns	*	**	ns
Comparisons																
A-B	ns	*	**	**	**											
A-C	ns	**	**	**	**											
A-E	ns	**	**	**	**											
B-C	ns	ns	ns	ns	ns											
B-E	ns	ns	**	ns	**											
C-E	ns	ns	ns	ns	ns											

TABLE C-16. RELATIONSHIP AMONG MEANS FOR RUN-ORDER BY CHANNEL LEG VOS (KNOTS)

	Channel Leg					Interaction	Comparisons									
	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
Run-Order																
1	7.52	7.23	5.92	4.68	3.35	0.01	ns	**	**	**	**	**	**	**	**	**
2	8.67	7.51	6.41	5.11	3.80		**	**	**	**	**	**	**	**	**	**
3	8.81	7.24	6.45	5.49	4.37		**	**	**	**	**	**	**	**	**	**
4	9.50	7.44	6.39	5.61	4.03		**	**	**	**	**	**	**	*	**	**
Comparisons																
1-2	**	ns	ns	ns	ns											
1-3	**	ns	ns	*	ns											
1-4	**	ns	ns	**	**											
2-3	ns	ns	ns	ns	ns											
2-4	**	ns	ns	ns	ns											
3-4	*	ns	ns	ns	ns											

TABLE C-17. RELATIONSHIP AMONG MEANS FOR RUN-ORDER BY CHANNEL LEG TOTAL RUDDER COMMANDS (#/MINUTES)

	Channel Leg					Interaction	Comparisons									
	1	2	3	4	5	p <	1-2	1-3	1-4	1-5	2-3	2-4	2-5	3-4	3-5	4-5
Run-Order																
1	1.86	1.78	1.66	1.60	1.37	0.05	ns	ns	ns	*	ns	ns	ns	ns	ns	ns
2	2.34	1.95	1.58	1.87	1.08		*	**	**	**	ns	ns	**	ns	*	**
3	2.13	1.61	1.63	2.02	1.15		**	**	ns	**	ns	*	*	*	*	**
4	2.04	1.72	1.52	1.92	1.17		ns	**	ns	**	ns	ns	**	*	ns	**
Comparisons																
1-2	*	ns	ns	ns	ns											
1-3	ns	ns	ns	*	ns											
1-4	ns	ns	ns	ns	ns											
2-3	ns	ns	ns	ns	ns											
2-4	ns	ns	ns	ns	ns											
3-4	ns	ns	ns	ns	ns											

TABLE C-18. CONFIDENCE INTERVAL (95%) FOR ROOT MEAN SQUARE - OFF-TRACK DEVIATION AND CONSISTENCY

Ship Type	Leg	Root Mean Square Off-Track Deviation (Feet)	Consistency (Feet)
A	2	$90.2 \leq \mu_O \leq 164.6$	$50.3 \leq \mu_O \leq 94.6$
		$51.6 \leq \sigma_O \leq 108.0$	$30.7 \leq \sigma_O \leq 64.2$
	3	$75.2 \leq \mu_O \leq 114.6$	$59.0 \leq \mu_O \leq 91.7$
		$27.4 \leq \sigma_O \leq 57.3$	$22.7 \leq \sigma_O \leq 47.5$
	4	$167.2 \leq \mu_O \leq 208.8$	$109.0 \leq \mu_O \leq 163.3$
		$28.9 \leq \sigma_O \leq 60.5$	$37.7 \leq \sigma_O \leq 78.9$
	Turn	$159.1 \leq \mu_O \leq 263.3$	$80.1 \leq \mu_O \leq 129.6$
		$72.3 \leq \sigma_O \leq 151.4$	$34.3 \leq \sigma_O \leq 71.8$
	6	$122.4 \leq \mu_O \leq 163.3$	$103.2 \leq \mu_O \leq 140.9$
		$28.4 \leq \sigma_O \leq 59.4$	$26.2 \leq \sigma_O \leq 54.8$
	Total	$141.7 \leq \mu_O \leq 174.9$	$121.3 \leq \mu_O \leq 160.0$
		$23.1 \leq \sigma_O \leq 48.3$	$26.8 \leq \sigma_O \leq 56.2$
B	2	$88.4 \leq \mu_O \leq 148.4$	$57.5 \leq \mu_O \leq 94.8$
		$41.6 \leq \sigma_O \leq 87.1$	$25.9 \leq \sigma_O \leq 54.2$
	3	$55.0 \leq \mu_O \leq 89.3$	$42.5 \leq \mu_O \leq 66.8$
		$23.8 \leq \sigma_O \leq 49.8$	$16.9 \leq \sigma_O \leq 35.3$
	4	$103.5 \leq \mu_O \leq 153.8$	$68.8 \leq \mu_O \leq 103.6$
		$34.9 \leq \sigma_O \leq 73.1$	$24.1 \leq \sigma_O \leq 50.5$
	Turn	$60.7 \leq \mu_O \leq 136.5$	$27.4 \leq \mu_O \leq 60.5$
		$52.6 \leq \sigma_O \leq 110.0$	$22.9 \leq \sigma_O \leq 48.0$
	6	$50.0 \leq \mu_O \leq 85.6$	$43.8 \leq \mu_O \leq 78.7$
		$24.7 \leq \sigma_O \leq 51.7$	$24.2 \leq \sigma_O \leq 50.8$
	Total	$82.2 \leq \mu_O \leq 113.8$	$77.8 \leq \mu_O \leq 107.8$
		$21.9 \leq \sigma_O \leq 45.8$	$20.8 \leq \sigma_O \leq 43.5$

TABLE C-18. CONFIDENCE INTERVAL (95%) FOR ROOT MEAN SQUARE - OFF-TRACK DEVIATION AND CONSISTENCY (CONT)

Ship Type	Leg	Root Mean Square Off-Track Deviation (Feet)	Consistency (Feet)
C	2	$86.5 \leq \mu_0 \leq 159.2$	$53.2 \leq \mu_0 \leq 98.3$
		$50.4 \leq \sigma_0 \leq 105.6$	$31.3 \leq \sigma_0 \leq 65.5$
	3	$50.1 \leq \mu_0 \leq 73.6$	$33.6 \leq \mu_0 \leq 45.8$
		$16.3 \leq \sigma_0 \leq 34.0$	$8.5 \leq \sigma_0 \leq 17.8$
	4	$87.7 \leq \mu_0 \leq 126.7$	$59.4 \leq \mu_0 \leq 95.3$
		$27.1 \leq \sigma_0 \leq 56.6$	$24.8 \leq \sigma_0 \leq 52.0$
	Turn	$88.7 \leq \mu_0 \leq 150.1$	$35.5 \leq \mu_0 \leq 60.9$
		$42.6 \leq \sigma_0 \leq 89.1$	$17.6 \leq \sigma_0 \leq 36.8$
	6	$44.3 \leq \mu_0 \leq 59.2$	$37.0 \leq \mu_0 \leq 51.3$
		$10.4 \leq \sigma_0 \leq 21.7$	$9.9 \leq \sigma_0 \leq 20.7$
	Total	$76.1 \leq \mu_0 \leq 104.1$	$92.8 \leq \mu_0 \leq 72.5$
		$19.4 \leq \sigma_0 \leq 40.7$	$14.0 \leq \sigma_0 \leq 29.4$
E	2	$99.7 \leq \mu_0 \leq 164.1$	$68.5 \leq \mu_0 \leq 103.0$
		$44.7 \leq \sigma_0 \leq 93.5$	$24.0 \leq \sigma_0 \leq 50.1$
	3	$49.2 \leq \mu_0 \leq 80.8$	$27.8 \leq \mu_0 \leq 42.1$
		$21.9 \leq \sigma_0 \leq 45.8$	$9.9 \leq \sigma_0 \leq 20.7$
	4	$60.4 \leq \mu_0 \leq 87.8$	$44.3 \leq \mu_0 \leq 68.5$
		$19.0 \leq \sigma_0 \leq 39.8$	$16.8 \leq \sigma_0 \leq 35.1$
	Turn	$89.0 \leq \mu_0 \leq 148.6$	$23.1 \leq \mu_0 \leq 42.6$
		$41.3 \leq \sigma_0 \leq 86.5$	$13.5 \leq \sigma_0 \leq 28.3$
	6	$27.2 \leq \mu_0 \leq 43.2$	$20.0 \leq \mu_0 \leq 32.5$
		$11.1 \leq \sigma_0 \leq 23.2$	$8.6 \leq \sigma_0 \leq 18.1$
	Total	$72.2 \leq \mu_0 \leq 93.6$	$67.6 \leq \mu_0 \leq 84.8$
		$14.8 \leq \sigma_0 \leq 31.0$	$11.9 \leq \sigma_0 \leq 24.9$

TABLE C-19. ANOVA SOURCE TABLE (TOTALS)

Source	df	MS	F
Subjects	15	-	-
Ship (A)	3	$SS_{A}/3$	$MSA/MS_{Error\ A}$
Error A	45	$SS_{Error\ A}/45$	-

END

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